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Who leads Research Productivity Change? Guidelines for R&D policy makers

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Who leads Research Productivity Change? Guidelines for R&D policy makers

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Abstract

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1. Introduction

Public support to Research and Development (R&D) and technology transfer activities are totally incorporated into Spanish Science and Technology (S&T) policies. However, the evaluation of these activities is not fully internalized into the policy cycle yet. Furthermore, the evaluation processes carried out so far deal with the elaboration of static indicators which barely provide an accurate picture regarding the way the results of these activities are evolving over the time. In addition, many scholars claim that the structuralist-evolutionary context under which these sorts of policies are being built (Lipsey et al. 2005) need an alternative evaluation context different to the efficiency of outcomes in a return on investment sense (Potts 2007).

Another important claim that policy makers and scholars raise with respect to these activities' outcomes and impacts is the need for a long term perspective to be able to actually appreciate them into the territory. However, this is an issue that has not been extensively treated in the policy evaluation literature. Moreover, this totally fair claim implies that conventional short term—cross section— evaluation processes of these activities might render narrow results that do not shed light on issues that could be useful to establish guidelines for long run policy reorientations. Therefore an evaluation methodology that provides a dynamic overview on the evolution of R&D and technology transfer activities should be able to capture, on the one hand, the behavioral evolution (Buisseret et al. 1995) of the agents participating in the policy (i.e. the micro-level perspective) and the complexity of the economic order that S&T policies pose on any given innovation system on the other (i.e. the macro-level perspective).

The innovation system approach provides us with a holistic view of the framework where innovation processes takes place, by considering: (i) the individually oriented behaviour of the agents at the micro level (researchers, firms and R&D managers); (ii) their network interactions, which finally determine the characteristics of the system at the macro level; (iii) the extent to which the system complies with the policy goal of articulation, understood as the existence of strong and continuous relationships between agents, which should favor the production of innovation in itself (productivity levels).

This paper proposes a dynamic evaluation framework for a Spanish public policy supporting R&D and technology transfer activities within the food technology field based on efficiency and productivity measures. To offer this dynamic view on the impacts and outcomes that such policy has shown (and still is showing) we follow a threefold perspective: micro, meso and macro. The micro level perspective constitutes the focus of our study (research groups participating within the food technology field in Spain), the meso level represents the plane where the recommendations to be concluded from the study are to be applied (Spanish S&T policy), while the macro level corresponds to the context of analysis (Spanish food innovation system).

Our goal is to determine the policy impact on the research groups' outputs (micro-level perspective) to gauge to what extent the policy contributes to consolidate the research groups´ position on the food technology field (meso-level perspective) and how this relative position is helping the policy to construct a complex and articulated innovation system on the referred field (macro-level perspective). That is, we aim to contribute to the literature with a dynamic framework that could offer a set of guidelines for decision-makers involved in the management of multi-level S&T policies.

Studying the evolution of the system in time implies determining the characteristics of the most successful agents from a dynamic perspective—which in turn implies sorting them out according to their heterogeneity, so as to categorize those best practices that allow R&D managers to change policy guidelines in a way that encourages less successful agents to adopt benchmark practices. Our study performs such dynamic analysis and the results provide R&D managers with consistent evidence of those best practices over time, which will allow them to design and implement new strategies (financial schemes and their associated requirements) that would render the system more efficient and productive.

In order to accomplish this target, we perform a Malmquist Productivity Index (MPI) analysis that help us understand how the policy is affecting the research groups participating into this policy. In this particular case, the paper focuses on the research groups within the food technology sector that belong to the Spanish National Research Council (CSIC) and that have participated in the Spanish Food Technology Program (SFTP) between 1988 and 1999. We explore how our methodological approach, from a dynamic perspective, allows to: (i) analyze and better understand the behaviour and interactions of agents within the innovation system, and their effect on the productivity; (ii) contribute to policy evaluation and the sort of recommendations that will emerge under this approach.

From this micro-level perspective, our analysis is able to capture the degree of heterogeneity among research groups, both in terms of their research behaviour and productive scale -i.e., relative size. This fact combined with the dynamic perspective helps us characterize the contribution of research groups to the articulation of the innovation system as the final policy goal from the macro-level perspective. However, policymakers do act in the meso-level (Dopfer et al., 2004). Hence, our conclusions are addressed to provide them with guidelines in terms of what characteristics allow research groups to increase their internal capabilities and how that evolution fosters the innovation system towards an articulated one. Therefore policymakers can reorient and adjust the policy in specific directions that provide agents with the incentives to change in desired direction. This is in fact the case of R&D managers in the food technology field, whose policy guidelines regarding the funding of particular projects and research groups have changed over the years in a way that is consistent with our results by promoting research activities of groups performing multidimensional and comprehensive research that contribute to the articulation of the innovation system, and exhibit higher efficiency and productivity levels.

The paper is structured as follows. The next section discusses the approaches that have been proposed in the literature to assess the dynamics of an innovation system and the policies related to it. This is followed by a discussion of the institutional framework that characterizes the Spanish Food Technology Programme (SFTP) and the research units participating in it. Next, we present the technology and its representation by way of the generalized distance function. In section 5 we present the alternative decompositions proposed in the literature to determine the contribution that technological change and efficiency change make to productivity change. On it, we rely on the interpretation that Zofío (2007) makes of the alternative terms in which the Malmquist Productivity Index (MPI) can be decomposed. The decompositions of the MPI found in the literature are based on a changing base approach, whose main consequence is that the indices do not comply with the circularity property that allow consistent aggregation of period by period and sub-period productivity changes. To avoid this weakness that would not allow us to carry out a dynamic analysis, we introduce the necessary chained index definitions of all the alternative decompositions. In section 6 we concisely present the Data Envelopment Analysis (DEA) techniques that allow calculation of the generalized distance functions on which the MPI is based. We undertake our empirical analysis of productivity change in section 7, where the productivity trends of the different research units involved in the SFTP are presented and the different sources of productivity change discussed. Finally, section 8 concludes illustrating to what extent the SFTP has fostered productivity growth among those research units that have obtained financial support within the Spanish R&D plan.

2. Public policies and the promotion of research: towards a dynamic assessment

Arguments in the field of economics of science and technological change that favour public intervention are mainly responding to two opposite streams within this literature: the Neoclassical, and the Structuralist-evolutionary. According to the former theoretical approach, public intervention rests on the existence of market failures; production of new knowledge is associated with a positive externality and thus public R&D policies are justified (Arrow 1962). The latter approach sees knowledge as an imperfect good that does not satisfy the usual characteristic of non-excludability (David et al. 1994). If we accept the non-rival nature of knowledge, the agents generating it will only be able to appropriate a small fraction of the social benefit produced, and therefore it will be necessary to promote R&D activities above optimal market levels, thus, justifying public policies to support these activities. This approach is also linked to the systemic view of the innovation process. Systemic analysis of innovation uses the concept of Innovation System (IS) to justify the existence of different agents, and the relationships among them, to carry out innovation activities (see, e.g., Freeman 1987; Lundvall 1992). Therefore, under a structuralist-evolutionary approach R&D public policies, to an extent, respond to the need to strengthen the role and involvement of IS agents (Lipsey and Carlaw 1998; Metcalfe 2002).

We rely on the idea and terminology of IS's articulation as introduced by Rip and Nederhof

(1986), to assess the Spanish Food Innovation System's (SFIS) capacity to establish a network of fluent and continuous knowledge flows among its constituting agents. Their concept of articulation correlates with the description in Gibbons et al. (1994) of the change over in scientific knowledge production from mode I—summarized as the pursuit of scientific truth by scientists—to mode II—the production of knowledge from application—and the subsequent role of relationships among agents to generate new and economically viable knowledge. Hence an articulated IS enables the different types of agents (policy makers, scientists, technologists, business men, etc.) to maintain continuity in their relationships, over time.

As pointed out above, in this paper we will focus on the impact that the Spanish Food Technology Program has had on the research groups within the food technology field in Spain, as one of the most relevant instruments used by Spanish S&T policies to encourage and support the articulation of the IS. From this perspective we want to link the idea of public policies promoting a growing multidimensional output of research units, as an instrumental policy goal toward the articulation of a successful IS. To assess whether this instrumental goal has been successful we evaluate such policy using productivity analysis. In particular, we will analyze the productivity gains observed in the research groups that belong to the CSIC. Our research question is thus: to what extent has the SFTP become a suitable tool to promote the productivity increases of research units (micro level) contributing therefore to a multidimensional research output mix and, by extension, to the SFIS's articulation (meso level)?

From our point of view, one of the main limitations of the existing studies on the evaluation of innovation is the static view they offer. The literature agrees that innovation is a dynamic phenomenon (Autio, 1997) and there is still a strong need to study the dynamics of technological change (ibid: 1474; Grimpe and Sofka, 2007). Lee and von Tunzelman (2005) consider that the study of system dynamics allows for the analysis of the behaviour of complex systems that aims to demonstrate how policies, decisions, structure, and delays are interrelated and influence growth and stability. In recent years, there have been attempts to provide the IS approach with a more dynamic view. Markard and Truffer (2008) following an actor-oriented view, relate the micro (individual strategies and resources) and meso (system characteristics) levels in the case of in the case of stationary fuel cells in Germany. Similarly, Miettinen (1999) illustrates the possibilities of studying the dynamics of research-driven innovations using activity and actor-network theories. In addition, the literature discerns a series of functions accomplished within the frame of IS as one of the main attempts to characterize these system dynamics (Balzat and Hanusch, 2004). In contrast to the traditional agent-based view of innovation, which mainly focuses on the structure or a certain system, the functions view of innovation is based on mapping the activities that result in technological change and finally in the performance of an IS (Hekkert et al., 2007; Bergek et al., 2008; Edquist and Hommen, 2008).

However, not only the dynamic assessment of an IS becomes a key issue, but also that of the innovation policies supporting its future development. In fact, the evolution followed by the IS approach and science, technology and innovation policies show an interactive and co-evolving process (Mytelka and Smith, 2002; Molas-Gallart and Davies, 2006). Accordingly, the innovation policy evaluation related literature is also challenged by the need to provide policy evaluations with a dynamic view (Arbel, 1981; van Raan, 2000; Kuhlmann, 2003). This change in the role of evaluation in policymaking has also implications in the rationales for intervention, the behaviour of institutions and framework conditions, and last but not least the role of the policymaker (Arnold, 2004).

From a science management perspective few are the efforts done in the evaluations of the innovation policy instruments implemented so as to dynamically analyse/measure their influence, both on the actors the policy is oriented to (micro level) and on the conclusions that may be drawn on the policy (meso) level. From the point of view of education policies, a recent contribution is Grammatikopoulos et al. (2004) who follow a dynamic evaluation approach in the field of education in Greece. Similarly, Schmidt et al. (2003) conclude about the organization and leadership of research environments; the framework and the conditions for research; and the resource allocation policy as the key drivers of research policies in Denmark. From the firms' perspective, one of the few contributions is that of Laitinen (2002) who presents the results of a dynamic integrated performance measurement system applied to small Finnish technology companies[1].

This is precisely our major target, to provide policymakers with a tool to dynamically assess the performance of the research units the policy is aimed at.

3. The Spanish Food Technology Programme institutional framework

The SFTP was launched in 1988 within the 1st national R&D plan and has been an element in all its subsequent announcements[2]. Its financial support represents around 5% of the overall national R&D Plan budget (Jiménez-Sáez 2005). Thus, based on the amount of resources devoted to SFTP, the importance of evaluating it in order to assess whether and to what extent its original objectives have been achieved is evident. Moreover, if the evaluation in this study proves useful it could serve as a model for the other programmes within the plan. In addition, this investigation will complement other analyses and evaluations in this context (Acosta Ballesteros and Modrego Rico 2001) and will contribute to filling the gap in Spanish R&D public policy evaluation (Bustelo 2006).

The SFTP as set forth in the original 1988 call was defined as a:

> systematic group of research and development projects oriented towards the encouragement of research, technology innovation and development in the Spanish Food Technology sector. It is co-ordinated and complemented by other actions among which the training of specialized

[1] For a more theoretical contribution about how to carry out a dynamic evaluation, the reading of Abbring and Heckman (2008) is recommended.

[2] In the last National Research, Development and Innovation Plan 2008-2011, the SFTP has adopted a new

personnel[3] and the establishment of an infrastructure that favours technology transfer from knowledge producing sectors to users stand out. (CICYT 1988)

Four major milestones constitute the central goal of the SFTP: *(i) training personnel; (ii) support for firm R&D and innovation activities; (iii) support for research groups' R&D activities; and (iv) support for technology transfer from research groups to firms* (CICYT 1987). The SFTP, as other R&D Programmes within the Spanish R&D plan—as well as in many other countries having similar programmes, was designed to cover all the stages in the innovation process, offering possibilities for participation to a wide variety of agents, and fostering co-operation among them. The present study focuses on the support for research group's R&D activities, which is mainly intended to provide financial support to research groups at public research organizations in order to carry out applied research mainly embodied in international scientific publications, scientific personnel training, patent applications, etc. as the most relevant measurable outputs concerning scientific productivity.

The initial budget for the Programme announced in 1988 was approximately €45 million. The highest share of this budget was earmarked for the creation of infrastructures (€14.7 million, 33% of the total budget), and support for R&D activities through a variety of financial tools (€12 million, 26.7%). Support for R&D activities carried out by research groups at Public Research Organizations (PRO) was assigned to *R&D projects* whose commercial potential would be of interest to private firms. In addition, there was the possibility of cooperation between research groups and firms through *bilateral contracts,* which existed outside the SFTP financial scheme. It was expected that both sources of financial support would translate into a multidimensional research output that would eventually render not only science-technology outputs, but also training and socio-economic goals related to a trustful and lasting cooperation with the private sector.

4. Technology and the Generalized Distance Function

Consider a panel of $i = 1,...,I$ research units observed in $t = 1,...,T$ periods, transforming input vectors $x_i^t = (x_{1i}^t, ..., x_{Ni}^t) \in \Re^N_+$ into output vectors $y_i^t = (y_{1i}^t, ..., y_{Mi}^t) \in \Re^M_+$. Given these data, technology can be represented by the production possibility set of feasible input-output combinations: $T^t = \{(x, y)$: x can produce y at time $t\}$, $t = 1,\ldots,T$, which satisfies the usual Shephard (1970) or Färe and Primont (1995) axioms. For i-th research unit, the production technology can be represented the generalized distance function introduced by Chavas and Cox (1999):

$$D_G^t(x,y;\alpha) = \min\left\{\delta > 0 : (x\delta^{1-\alpha}, y/\delta^{\alpha}) \in T^t\right\}, \quad x \in \Re_+^N, \; y \in \Re_+^M \tag{1}$$

name, "Agrarian and Food Biotechnology", which is included in the strategic line of biotechnology.

[3] The SFTP originally included in the training of specialized personnel two different outputs: young researchers (grant holders) finalizing their PhD (thesis writing) and technical support personnel. The data for the analysis in this paper accounts for both these categories as completed PhD theses and technical trained personnel.

where $0 \leq \alpha \leq 1$ represents the relative weight that the distance function places on outputs and inputs—a balanced weight is given by $\alpha = 0.5$ as $\alpha/(1-\alpha) = 1$. It inherits its name from the fact that thanks to the α parameter it encompasses the partially oriented output and input distance functions, as well as the hyperbolic graph distance function introduced by Färe et al. (1985: 46). When $\alpha = 1$, the generalized distance function equals the output distance function $D_{\mathrm{O}}^{t}(x^{t}, y^{t}) = \min\{\phi > 0 : (x, y/\phi) \in \mathrm{T}^{t}\}$, $x \in \Re_{+}^{\mathrm{N}}$, $y \in \Re_{+}^{\mathrm{M}}$, while if α=0 it is equivalent to the input distance function, $D_{\mathrm{I}}^{t}(x^{t}, y^{t}) = \max\{\gamma > 0 : (x/\gamma, y) \in \mathrm{T}^{t}\}$, $x \in \Re_{+}^{\mathrm{N}}$, $y \in \Re_{+}^{\mathrm{M}}$. Finally, if α=0.5 equation (1) becomes the square of the hyperbolic graph distance function: $D_{\mathrm{H}}^{t}(x^{t}, y^{t}) = \min\{\theta > 0 : (x\theta, y/\phi) \in \mathrm{T}^{t}\}$, $x \in \Re_{+}^{\mathrm{N}}$, $y \in \Re_{+}^{\mathrm{M}}$. It is clear that (1) allows assigning asymmetric weights to the inputs and outputs vectors depending on the choice of α, which is exogenously determined in the model. As we do not want to stress one particular dimension of the production process when measuring research efficiency, in this study we decide for a neutral direction that equally weights inputs contraction and outputs expansion, i.e. $\alpha = 0.5$. Chavas and Cox (1999: 300) prove that if the technology satisfies the standard axioms, then (i) $\mathrm{D_G}(x, y; \alpha) \leq 1$, (ii) it is almost homogeneous in degree $(\alpha-1)$, α and 1 in x and y, and (iii) it is non-decreasing in outputs and non-increasing in inputs. The generalized distance function places a research group on the *best practice* frontier represented by the boundary of the technology –defined as Isoq $\mathrm{T}^{t} = \{(x, y): (x, y) \in \mathrm{T}^{t}, (\omega^{1-\beta}x, y/\omega^{\beta}) \notin \mathrm{T}^{t}, 0<\omega<1, 0 \leq \beta \leq 1\}$, and can be interpreted as a measure of *technical* efficiency in the sense of Farrell (1957). Therefore, if $D_{\mathrm{G}}^{t}(x^{t}, y^{t}; \alpha) = 1$ for a particular research unit, this observation is efficient, belonging to Isoq T^{t}, while if $D_{\mathrm{G}}^{t}(x^{t}, y^{t}; \alpha) < 1$ it is inefficient.

Besides variable returns to scale, the technology T^{t} may exhibit global increasing, decreasing and constant returns to scale. In this latter case the technology T^{t} implies a mapping $x \rightarrow y$ that is linearly homogeneous of degree +1, and may be denoted by $\hat{\mathrm{T}} = \{(\lambda x, \lambda y): (x,y) \in \mathrm{T}, \lambda > 0\}$, while the generalized distance function corresponds to:

$$\hat{D}_{\mathrm{G}}^{t}(x,y;\alpha) = \min\left\{\delta > 0 : (x\delta^{1-\alpha}, y/\delta^{\alpha}) \in \hat{\mathrm{T}}^{t}\right\},\ x \in \Re_{+}^{\mathrm{N}}, y \in \Re_{+}^{\mathrm{M}}. \quad (2)$$

This generalized distance function can be also interpreted as a measure of *productive* efficiency, placing an observation on the *benchmark* frontier represented by Isoq $\hat{\mathrm{T}}^{t} = \{(x,y): (x,y) \in \hat{\mathrm{T}}^{t}, (\omega^{(1-\beta)}x, y/\omega^{\beta}) \notin \hat{\mathrm{T}}^{t\ t}, 0<\omega<1, 0 \leq \beta \leq 1\}$—with the same numeric interpretation as its technical counterpart (2). When global returns to scale hold the generalized distance function is homogeneous of degree zero in inputs and outputs: $\hat{D}_{\mathrm{G}}^{t}(\lambda x^{t}, \lambda y^{t}; \alpha) = \hat{D}_{\mathrm{G}}^{t}(x^{t}, y^{t}; \alpha)$, $\lambda>0$.

Clearly, whether the technology exhibits constant or variable returns to scale is to be determined with the sample data. However, if one assumes that the technology exhibits variable returns to scale, any Malmquist index based on the corresponding distance functions would not be regarded as a productivity index. Then, how can it be ensured that a MPI would satisfy the desirable homogeneity properties in outputs and inputs while retaining at the same time the variable returns to scale assumption on the technology? By defining distance functions that would compare productive performance to a benchmark linearly homogeneous technology which enhances such comparison from technical efficiency to include scale efficiency, *i.e.* which gauge productive efficiency and can be decomposed so as to determine the contribution that scale efficiency and returns to scale make to productive change—as discussed in the following section. Balk (2001)—generalized by Zofío and Prieto (2006)—shows that this comparison corresponds to the distance function (2) defined on the supporting—virtual— technology characterized by global returns to scale, which is equivalent to measure productive efficiency against units operating at the most productive scale sizes (MPSSs), and whose productions processes characterize by local constant returns to scale.

Relaying on these definitions, any difference between the variable (1) and constant returns to scale (2) distance functions can be interpreted as a measure of scale efficiency: $\mathrm{SE}^t\,(x^t, y^t;\alpha)$ = $\mathrm{PE}^t(x^t, y^t;\alpha)\ /\ \mathrm{TE}^t(x^t, y^t;\alpha) = \hat{D}^t_{\mathrm{G}}(x^t, y^t;\alpha)\ /\ D^t_{\mathrm{G}}(x^t, y^t;\alpha)$.

5. Decomposing the Malmquist productivity index (MPI)

The Malmquist index is a ratio of two distance functions representing the change in productivity of a research unit relative to the benchmark technologies existing in two consecutive periods. Therefore the contemporary definition of the generalized distance function needs to be adapted to such mix-period representation. With regard to the characterization of technology, it is now commonly acknowledged in the literature that in order to be interpreted as a *productivity* index, the distance functions comprising the Malmquist ratio must be defined on the constant returns to scale production technology (2). Førsund (1997) summarizes this axiomatic approach to acknowledge any index as a *productivity* index, but the most relevant one in our current Malmquist framework is the proportionality property. This property states that if outputs (inputs) are increased (decreased) in the same proportion from one period to the next while inputs (outputs) remain the same, then the productivity index must increase (decreased) in the same proportion. When dealing with MPI this property requires that the generalized distance functions comprising it must be linearly homogeneous of degree +1 in outputs and –1 inputs, *i.e.* the benchmark technology characterizes by constant returns to scale and the Malmquist index can considered as a productivity index by complying with the desirable proportionally property, see also Färe and Grosskopf (1996:54, proposition 3.2.6).

However, the fact that the supporting technology to correctly define productivity indices requires constant returns to scale does not mean that the underlying technology may not exhibit variable returns to scale. In fact, when identifying the contribution of returns to scale and scale efficiency one implicitly assumes that these terms are relevant sources of productivity change and, therefore, must be included in the analysis. Hence we begin this section presenting the decomposition independently introduced by Simar and Wilson (1998) and Zofío and Lovell (1998) –hereafter jointly denoted by SWLZ (1998)– and show that the two remaining proposals identifying the role that scale plays in productivity change can be recovered from it—namely Färe *et al.* (1994) and Ray and Desli (1997), providing a unifying framework where one may deal with a complete characterization of technological and efficiency change. In the light of this contribution we rely on a comprehensive decomposition of the MPI whose terms can be correctly interpreted by retaining and complying with generally accepted definitions commonly accepted in the literature. Finally, the following presentation of the MPI and its complementary decompositions depart from the usual definition of adjacent time-periods productivity changes referred to a changing base, and consider a fixed-base technology as benchmark. While the standard approach updates the base from period to period, the latter retains the same base period throughout the entire time span. Berg et al. (1992) and Førsund (1993) note that in the latter case the index itself and its components satisfy Frisch's (1936) circular test, therefore allowing consistent decomposition or build–ups of productivity change in different but complementary sub-periods. In long range studies as the one we perform here it seems appropriate to calculate productivity change relative to a fixed–base reference technology thus allowing productivity trends comparisons between subsequent periods.

We start out with the adjacent-period version of the fixed-based MPI. For any given unit i observed in two consecutive periods, (x_i^t, y_i^t) and (x_i^{t+1}, y_i^{t+1}), and using the first period t=1 as the base technology, the fixed-based MPI defines as[4]:

$$\hat{\mathrm{M}}_{\mathrm{G}}^{1}\,(x_i^t, y_i^t, x_i^{t+1}, y_i^{t+1};\alpha) = \frac{\hat{D}_{\mathrm{G}}^{1}\left(x_i^{t+1}, y_i^{t+1};\alpha\right)}{\hat{D}_{\mathrm{G}}^{1}\left(x_i^{t}, y_i^{t};\alpha\right)}, \qquad (3)$$

where the mix period generalized distance functions $\hat{D}_{\mathrm{G}}^{1}\left(x_i^{t}, y_i^{t};\alpha\right)$ and $\hat{D}_{\mathrm{G}}^{1}\left(x_i^{t+1}, y_i^{t+1};\alpha\right)$ define in an analogous way to (2). Taking the former as the illustrating case, it defines as $\hat{D}_{\mathrm{G}}^{1}\left(x_i^{t}, y_i^{t};\alpha\right)$ = $\min\left\{\delta > 0 : (x_i^t\delta^{1-\alpha}, y_i^t / \delta^{\alpha}) \in \hat{\mathrm{T}}^1\right\}$, $x \in \Re_{+}^{\mathrm{N}}, y \in \Re_{+}^{\mathrm{M}}$, which compares subsequent periods research units to the base period technology.

However, while the MPI version presented in (3) ensures that the index satisfies the circular text, it does not yield values cumulating throughout the whole period, but temporal trends corresponding to period to period variations —even if refereed to the base year, whose interpretation is not as straightforward as keeping a reference period constant. Thus if any consecutive indices, e.g. $\hat{\mathrm{M}}_{\mathrm{G}}^{1}$ (1,2) and $\hat{\mathrm{M}}_{\mathrm{G}}^{1}$ (2,3) calculated as in (3), are multiplied, one would get $\hat{\mathrm{M}}_{\mathrm{G}}^{1}$ (1,3), yielding the following cumulative version of the fixed-base MPI:

[4] It can be easily proved that the desirable proportionally property is satisfied by (6), *i.e.* $\hat{\mathrm{M}}_{\mathrm{G}}^{1}\,(x_i^1, y_i^1, x_i^t, y_i^t) = \mathrm{M}_{\mathrm{G}}^{1}(x_i^1, y_i^1, \mu x_i^t, \nu y_i^t) = \mu/\nu$.

$$\hat{\mathrm{M}}_{\mathrm{G}}^{1}\ (x_i^1, y_i^1, x_i^t, y_i^t;\alpha) = \frac{\hat{D}_{\mathrm{G}}^{1}\left(x_i^t, y_i^t;\alpha\right)}{\hat{D}_{\mathrm{G}}^{1}\left(x_i^1, y_i^1;\alpha\right)}, \tag{4}$$

where the distance functions define as above. We now present the alternative ways in which (4) can be decomposed according to the alternative proposals suggested in the literature—while following Zofío and Lovell (2001) it would be possible to obtain the counterparts corresponding to (3), which are used in the empirical application to discuss productivity change between periods.

5.1. First level decomposition of the chained MPI: technical and efficiency change

For $\hat{D}_{\mathrm{G}}^{1}\left(x_i^t, y_i^t;\alpha\right)$ it can be the case that $\left(x_i^t, y_i^t\right) \notin \hat{\mathrm{T}}^1$. As a result values of $\hat{D}_{\mathrm{G}}^{1}\left(x_i^t, y_i^t\right) > 1$ would be verified in the presence of technological progress, whose contribution to (4) can be singled out through the following decomposition:

$$\begin{aligned}\hat{\mathrm{M}}_{\mathrm{G}}^{1}\ (x_i^1, y_i^1, x_i^t, y_i^t;\alpha) &= \frac{\hat{D}_{\mathrm{G}}^{1}\left(x_i^t, y_i^t;\alpha\right)}{\hat{D}_{\mathrm{G}}^{1}\left(x_i^1, y_i^1;\alpha\right)} = \frac{\hat{D}_{\mathrm{G}}^{1}\left(x_i^t, y_i^t;\alpha\right)}{\hat{D}_{\mathrm{G}}^{t}\left(x_i^t, y_i^t;\alpha\right)} \cdot \frac{\hat{D}_{\mathrm{G}}^{t}\left(x_i^t, y_i^t;\alpha\right)}{\hat{D}_{\mathrm{G}}^{1}\left(x_i^1, y_i^1;\alpha\right)} = \\ &= \mathrm{PTC}_{\mathrm{G}}^{1,t}\left(x_i^t, y_i^t;\alpha\right) \cdot \mathrm{EC}_{\mathrm{G}}^{1,t}\left(x_i^1, y_i^1; x_i^t, y_i^t;\alpha\right).\end{aligned} \tag{5}$$

Following Färe et al. (1994a)—extended in Färe et al. (1994b), hereafter FGNZ—technical change $\mathrm{PTC}_{\mathrm{G}}^{1,t}\left(x_i^t, y_i^t;\alpha\right)$, and efficiency change $\mathrm{EC}_{\mathrm{G}}^{1,t}\left(x_i^1, y_i^1, x_i^t, y_i^t;\alpha\right)$ can be interpreted as follows: $\mathrm{PTC}_{\mathrm{G}}^{1,t}\left(x_i^t, y_i^t;\alpha\right)$ would capture the shift in the technology between the periods 1 and t using the fixed benchmark frontier as reference, while $\mathrm{EC}_{\mathrm{G}}^{1,t}\left(x_i^1, y_i^1, x_i^t, y_i^t;\alpha\right)$ would measure the change in relative efficiency, *i.e.* how far observed production is from maximum potential production. However, Griffel-Tatjé and Lovell (1999) and Ray and Desli (1997) –hereafter RD– argue against the technical change interpretation since its commonly accepted definition refers to shifts in the production technology for a given scale and not changes in the supporting virtual technologies. Zofío (2007) shows that $\mathrm{PTC}_{\mathrm{G}}^{1,t}\left(x_i^t, y_i^t;\alpha\right)$ captures the change in potential technical change between units operating at the most productive scale sizes, MPSSs—where units are both technical and scale efficient—in two consecutive periods. We term it potential because is measures the maximum productivity change that could be achieved by any unit if it were fully efficient. Therefore $\mathrm{PTC}_{\mathrm{G}}^{1,t}\left(x_i^t, y_i^t;\alpha\right)$ may be viewed as the highest potential productivity change in the absence of inefficiency—either from technical or scale reasons—and therefore measures productivity change between the highest observed productivities in the two periods. On the other hand, equal reasoning applies to the efficiency change term, which truly measures how far a unit is from the benchmark cone productivity and the best practice variable returns to scale frontier, and therefore would comprise both technical and scale efficiency change terms –as FGNZ (1994) would render later on explicit in their enhanced and final decomposition.

5.2. Second level decomposition of the MPI: accounting for scale

The MPI (5) can be further decomposed by splitting potential technical change and efficiency change into four new terms that allow determining the contribution that returns to scale and scale efficiency change make to productivity change. These contributions can be determined by way of the so–called scale—bias—of technical change introduced by SWLZ (1998). Starting with $\mathrm{PTC}_{\mathrm{G}}^{1,t}\left(x_i^t, y_i^t;\alpha\right)$ measuring potential productivity change at the reference optimal scale over time from the i–th unit perspective, it can be decomposed as follows:

$$\begin{aligned}\mathrm{PTC}_{\mathrm{G}}^{1,t}\left(x_i^1, y_i^1, x_i^t, y_i^t;\alpha\right) &= \frac{D_{\mathrm{G}}^1\left(x_i^t, y_i^t;\alpha\right)}{D_{\mathrm{G}}^t\left(x_i^t, y_i^t;\alpha\right)} \cdot \frac{\hat{D}_{\mathrm{G}}^1\left(x_i^t, y_i^t;\alpha\right) / D_{\mathrm{G}}^1\left(x_i^t, y_i^t;\alpha\right)}{\hat{D}_{\mathrm{G}}^t\left(x_i^t, y_i^t;\alpha\right) / D_{\mathrm{G}}^t\left(x_i^t, y_i^t;\alpha\right)} = \\ &= \mathrm{TC}_{\mathrm{G}}^{1,t}\left(x_i^t, y_i^t;\alpha\right) \cdot \mathrm{STC}_{\mathrm{G}}^{1,t}\left(x_i^t, y_i^t;\alpha\right) = \\ &= \frac{D_{\mathrm{G}}^1\left(x_i^t, y_i^t;\alpha\right)}{D_{\mathrm{G}}^t\left(x_i^t, y_i^t;\alpha\right)} \cdot \frac{\hat{D}_{\mathrm{G}}^1\left(x_i^t, y_i^t;\alpha\right) / \hat{D}_{\mathrm{G}}^t\left(x_i^t, y_i^t;\alpha\right)}{D_{\mathrm{G}}^1\left(x_i^t, y_i^t;\alpha\right) / D_{\mathrm{G}}^t\left(x_i^t, y_i^t;\alpha\right)} = \\ &= \mathrm{TC}_{\mathrm{G}}^{1,t}\left(x_i^t, y_i^t;\alpha\right) \cdot \mathrm{PTC}_{\mathrm{G}}^{1,t}\left(x_i^t, y_i^t;\alpha\right) / \mathrm{TC}_{\mathrm{G}}^{1,t}\left(x_i^t, y_i^t;\alpha\right),\end{aligned} \tag{6}$$

where $\mathrm{TC}_{\mathrm{G}}^{1,t}\left(x_i^t, y_i^t;\alpha\right)$ captures the shift in the best practice variable returns to scale frontier technology from the unit's comparison period t perspective, and $\mathrm{STC}_{\mathrm{G}}^{1,t}\left(x_i^t, y_i^t;\alpha\right)$ represents the scale bias against or in favor of the reference research unit scale. This can be easily shown rearranging $\mathrm{STC}_{\mathrm{G}}^{1,t}\left(x_i^t, y_i^t;\alpha\right)$ as in the third line of (6). The numerator corresponds to potential technical change at optimal scale while the denominator corresponds to productivity change coming from technical change at the reference scale, *i.e.* $\mathrm{STC}_{\mathrm{G}}^{1,t}\left(x_i^t, y_i^t;\alpha\right) = \mathrm{PTC}_{\mathrm{G}}^{1,t}\left(x_i^t, y_i^t;\alpha\right) / \mathrm{TC}_{\mathrm{G}}^{1,t}\left(x_i^t, y_i^t;\alpha\right)$.

Zofío (2007) extensively discusses how $\mathrm{STC}_{\mathrm{G}}^{1,t}\left(x_i^t, y_i^t;\alpha\right)$ can be soundly obtained from a production perspective. Here we just stress its numeric meaning. If $\mathrm{STC}_{\mathrm{G}}^{1,t}\left(x_i^t, y_i^t;\alpha\right) > 1$, productivity gains reflected by the technical change at the research unit's comparison period scale does not match the potential productivity change observed at the optimal scales—the change in the MPSSs from the base to the comparison period, and accordingly, technical change at the unit's scale has to be augmented with an additional productivity gain if it is to match that one at optimal scale. Therefore, we can conclude that the change in the technology with regard to optimal scale presents a bias against the research unit's scale since it outgrows technical change at the research unit's particular scale —*i.e.* the change in the reference optimal scale works against the unit's scale with regard to productivity change, which would be the interpretation for $\mathrm{STC}_{\mathrm{G}}^{1,t}\left(x_i^t, y_i^t;\alpha\right)$ when expressed as in the first line of (6). Contrarily, when $\mathrm{STC}_{\mathrm{G}}^{1,t}\left(x_i^t, y_i^t;\alpha\right) < 1$, productivity change at the reference scale exceeds productivity change at the optimal scale, and consequently technical change has to be decreased in the amount necessary to match productivity change at optimal scale. Therefore, the change in the technology with regard to optimal scale presents a bias in favor of the evaluated research unit's scale —*i.e.* the scale bias of technical change works in favor of the unit's scale. Finally, $\mathrm{STC}_{\mathrm{G}}^{1,t}\left(x_i^t, y_i^t;\alpha\right)=1$ shows that the scale bias of technical change is neutral since productivity change at the reference scale matches productivity change at optimal scale, as would be the case in the presence of constant returns to scale.

We now decompose the efficiency change term $\mathrm{EC}_{\mathrm{G}}^{1,t}\left(x_i^1, y_i^1, x_i^t, y_i^t;\alpha\right)$ into the following terms:

$$
\begin{aligned}
\mathrm{EC}_{\mathrm{G}}^{1,t}\left(x_i^1, y_i^1, x_i^t, y_i^t;\alpha\right) &= \frac{D_{\mathrm{G}}^t\left(x_i^t, y_i^t;\alpha\right)}{D_{\mathrm{G}}^1\left(x_i^1, y_i^1;\alpha\right)} \cdot \frac{\hat{D}_{\mathrm{G}}^t\left(x_i^t, y_i^t;\alpha\right) / D_{\mathrm{G}}^t\left(x_i^t, y_i^t;\alpha\right)}{\hat{D}_{\mathrm{G}}^1\left(x_i^1, y_i^1;\alpha\right) / D_{\mathrm{G}}^1\left(x_i^1, y_i^1;\alpha\right)} = \\
&= \mathrm{TEC}_{\mathrm{G}}^{1,t}\left(x_i^1, y_i^1, x_i^t, y_i^t;\alpha\right) \cdot \mathrm{SEC}_{\mathrm{G}}^{1,t}\left(x_i^1, y_i^1, x_i^t, y_i^t;\alpha\right),
\end{aligned}
\tag{7}
$$

where $\mathrm{TEC}_{\mathrm{G}}^{1,t}\left(x_i^1, y_i^1, x_i^t, y_i^t;\alpha\right)$ compares how a given unit varies its technical efficiency in time with regard to the best practice technology existing in the base and comparison periods. Recalling from the previous section the scale efficiency definition $\mathrm{SE}^t(x^t, y^t;\alpha) = \mathrm{PE}^t(x^t, y^t;\alpha) \;/\; \mathrm{TE}^t(x^t, y^t;\alpha) = \hat{D}_{\mathrm{G}}^t(x^t, y^t;\alpha) \;/\; D_{\mathrm{G}}^t(x^t, y^t;\alpha)$, the second term in the right hand side of (7), $\mathrm{SEC}_{\mathrm{G}}^{1,t}\left(x_i^1, y_i^1, x_i^t, y_i^t;\alpha\right)$, captures the change in scale efficiency from the base to the comparison period and with regard to the highest productivity attained at the optimal reference scales of both benchmark technologies.

Considering the decomposition of potential technical change (6) and efficiency change (7), it is possible to present the extended decomposition of the MPI proposed by SWLZ (1998):

$$
\begin{aligned}
\hat{\mathrm{M}}_{\mathrm{G}}^1\;(x_i^1, y_i^1, x_i^t, y_i^t;\alpha) &= \frac{D_{\mathrm{G}}^1\left(x_i^t, y_i^t;\alpha\right)}{D_{\mathrm{G}}^t\left(x_i^t, y_i^t;\alpha\right)} \cdot \frac{\hat{D}_{\mathrm{G}}^1\left(x_i^t, y_i^t;\alpha\right) / D_{\mathrm{G}}^1\left(x_i^t, y_i^t;\alpha\right)}{\hat{D}_{\mathrm{G}}^t\left(x_i^t, y_i^t;\alpha\right) / D_{\mathrm{G}}^t\left(x_i^t, y_i^t;\alpha\right)} = \\
&= \frac{D_{\mathrm{G}}^t\left(x_i^t, y_i^t;\alpha\right)}{D_{\mathrm{G}}^1\left(x_i^1, y_i^1;\alpha\right)} \cdot \frac{\hat{D}_{\mathrm{G}}^t\left(x_i^t, y_i^t;\alpha\right) / D_{\mathrm{G}}^t\left(x_i^t, y_i^t;\alpha\right)}{\hat{D}_{\mathrm{G}}^1\left(x_i^1, y_i^1;\alpha\right) / D_{\mathrm{G}}^1\left(x_i^1, y_i^1;\alpha\right)} = \\
&= \mathrm{TC}_{\mathrm{G}}^{1,t}\left(x_i^t, y_i^t;\alpha\right) \cdot \mathrm{STC}_{\mathrm{G}}^{1,t}\left(x_i^t, y_i^t;\alpha\right) \cdot \\
&\quad \cdot \mathrm{TEC}_{\mathrm{G}}^{1,t}\left(x_i^1, y_i^1, x_i^t, y_i^t;\alpha\right) \cdot \mathrm{SEC}_{\mathrm{G}}^{1,t}\left(x_i^1, y_i^1, x_i^t, y_i^t;\alpha\right).
\end{aligned}
\tag{8}
$$

5.3. Alternative decompositions of the MPI

We can now proceed to present the alternative decompositions of the MPI that have been proposed in the literature. We depart from the definition of the scale efficiency change in (7), which can be decomposed in the following terms:

$$
\begin{aligned}
\mathrm{SEC}_{\mathrm{G}}^{1,t}\left(x_i^1, y_i^1, x_i^t, y_i^t;\alpha\right) &= \frac{\hat{D}_{\mathrm{G}}^1\left(x_i^t, y_i^t;\alpha\right) / D_{\mathrm{G}}^1\left(x_i^t, y_i^t;\alpha\right)}{\hat{D}_{\mathrm{G}}^1\left(x_i^1, y_i^1;\alpha\right) / D_{\mathrm{G}}^1\left(x_i^1, y_i^1;\alpha\right)} \Big/ \frac{\hat{D}_{\mathrm{G}}^1\left(x_i^t, y_i^t;\alpha\right) / D_{\mathrm{G}}^1\left(x_i^t, y_i^t;\alpha\right)}{\hat{D}_{\mathrm{G}}^t\left(x_i^t, y_i^t;\alpha\right) / D_{\mathrm{G}}^t\left(x_i^t, y_i^t;\alpha\right)} = \\
&= \mathrm{RTS}_{\mathrm{G}}^1\left(x_i^1, y_i^1, x_i^t, y_i^t;\alpha\right) / \mathrm{STC}_{\mathrm{G}}^{1,t}\left(x_i^t, y_i^t;\alpha\right),
\end{aligned}
\tag{9}
$$

where the new term $\mathrm{RTS}_{\mathrm{G}}^{1}\left(x_i^1, y_i^1, x_i^t, y_i^t;\alpha\right)$ represents productivity variations coming from a change in the scale of the evaluated unit with respect to the base technology, *i.e.* returns to scale. $\mathrm{RTS}_{\mathrm{G}}^{1}\left(x_i^1, y_i^1, x_i^t, y_i^t;\alpha\right)$ corresponds to what RD (1997) initially referred to as scale efficiency change, as well as Grifell-Tatjé and Lovell (1999) and Balk (2001). However, the structure of this term clearly differs from the one in the first line of (7), as the latter uses a single period technology while scale efficiency change compares scale efficiency with regard to own period technologies, *i.e.* how the unit moves toward or away from optimal scale in both periods. In an interpretation that illustrates the nature of this term, Lovell (2003) makes use of discrete time formulations that identify it as a measure of the contribution of returns to scale to productivity change. In fact, to reinforce this interpretation of the first term in (9) let us consider the next alternative decomposition of the MPI (5):

$$\begin{aligned}\hat{\mathrm{M}}_{\mathrm{G}}^{1}\ (x_i^1, y_i^1, x_i^t, y_i^t;\alpha) &= \frac{\hat{D}_{\mathrm{G}}^{1}\left(x_i^t, y_i^t;\alpha\right)}{\hat{D}_{\mathrm{G}}^{1}\left(x_i^1, y_i^1;\alpha\right)} = \frac{D_{\mathrm{G}}^{1}\left(x_i^t, y_i^t;\alpha\right)}{D_{\mathrm{G}}^{1}\left(x_i^1, y_i^1;\alpha\right)} \cdot \frac{\hat{D}_{\mathrm{G}}^{1}\left(x_i^t, y_i^t;\alpha\right) / D_{\mathrm{G}}^{1}\left(x_i^t, y_i^t;\alpha\right)}{\hat{D}_{\mathrm{G}}^{1}\left(x_i^1, y_i^1;\alpha\right) / D_{\mathrm{G}}^{1}\left(x_i^1, y_i^1;\alpha\right)} = \\ &= \mathrm{M}_{\mathrm{G}}^{1}\ (x_i^1, y_i^1, x_i^t, y_i^t;\alpha) \cdot \mathrm{RTS}_{\mathrm{G}}^{1}\left(x_i^1, y_i^1, x_i^t, y_i^t;\alpha\right),\end{aligned} \tag{10}$$

which is the fixed-based version of the original Caves et al. (1982) Malmquist index, that does not comply with the desirable proportionally property, enhanced with the contribution of returns to scale to productivity change —see Grifell-Tatjé and Lovell (1999: 85). If $\mathrm{RTS}_{\mathrm{G}}^{1}\left(x_i^1, y_i^1, x_i^t, y_i^t;\alpha\right) > 1$, the unit improves its performance on a scale basis with regard to the base period productivity benchmark by exploiting increasing returns to scale and getting closer to the MPSS. Contrarily, $\mathrm{RTS}_{\mathrm{G}}^{1}\left(x_i^1, y_i^1, x_i^t, y_i^t;\alpha\right) < 1$ indicates that input change carries decreasing returns to scale and the unit is moving away from optimal scale. Finally, when $\mathrm{RTS}_{\mathrm{G}}^{1}\left(x_i^1, y_i^1, x_i^t, y_i^t;\alpha\right) = 1$, the unit does not profit (endure) from scale economies (diseconomies) as when constant returns to scale prevail over the input-output scale range.

By recalling the technical change and technical efficiency change terms already introduced in (6) and (9) we obtain the decomposition proposed by RD (1997):

$$\begin{aligned}\hat{\mathrm{M}}_{\mathrm{G}}^{1}\ (x_i^1, y_i^1, x_i^t, y_i^t;\alpha) &= \frac{D_{\mathrm{G}}^{1}\left(x_i^t, y_i^t;\alpha\right)}{D_{\mathrm{G}}^{t}\left(x_i^t, y_i^t;\alpha\right)} \cdot \frac{D_{\mathrm{G}}^{t}\left(x_i^t, y_i^t;\alpha\right)}{D_{\mathrm{G}}^{1}\left(x_i^1, y_i^1;\alpha\right)} \cdot \frac{\hat{D}_{\mathrm{G}}^{1}\left(x_i^t, y_i^t;\alpha\right) / D_{\mathrm{G}}^{1}\left(x_i^t, y_i^t;\alpha\right)}{\hat{D}_{\mathrm{G}}^{1}\left(x_i^1, y_i^1;\alpha\right) / D_{\mathrm{G}}^{1}\left(x_i^1, y_i^1;\alpha\right)} = \\ &= \mathrm{TC}_{\mathrm{G}}^{1,t}\left(x_i^t, y_i^t;\alpha\right) \cdot \mathrm{TEC}_{\mathrm{G}}^{1,t}\left(x_i^1, y_i^1, x_i^t, y_i^t;\alpha\right) \cdot \mathrm{RTS}_{\mathrm{G}}^{1}\left(x_i^1, y_i^1, x_i^t, y_i^t;\alpha\right)\end{aligned} \tag{11}$$

Finally, the initial decomposition of the MPI introduced by FGNZ (1994) departs from (7) by decomposing the efficiency change component:

$$\begin{aligned}\hat{\mathrm{M}}_{\mathrm{G}}^{1}\ (x_i^1, y_i^1, x_i^t, y_i^t;\alpha) &= \frac{\hat{D}_{\mathrm{G}}^{1}\left(x_i^t, y_i^t;\alpha\right)}{\hat{D}_{\mathrm{G}}^{t}\left(x_i^t, y_i^t;\alpha\right)} \cdot \frac{D_{\mathrm{G}}^{t}\left(x_i^t, y_i^t;\alpha\right)}{D_{\mathrm{G}}^{1}\left(x_i^1, y_i^1;\alpha\right)} \cdot \frac{\hat{D}_{\mathrm{G}}^{t}\left(x_i^t, y_i^t;\alpha\right) / D_{\mathrm{G}}^{t}\left(x_i^t, y_i^t;\alpha\right)}{\hat{D}_{\mathrm{G}}^{1}\left(x_i^1, y_i^1;\alpha\right) / D_{\mathrm{G}}^{1}\left(x_i^1, y_i^1;\alpha\right)} = \\ &= \mathrm{PTC}_{\mathrm{G}}^{1,t}\left(x_i^t, y_i^t;\alpha\right) \cdot \mathrm{TEC}_{\mathrm{G}}^{1,t}\left(x_i^1, y_i^1, x_i^t, y_i^t;\alpha\right) \cdot \mathrm{SEC}_{\mathrm{G}}^{1}\left(x_i^1, y_i^1, x_i^t, y_i^t;\alpha\right)\end{aligned} \tag{12}$$

It is important to remark that asking for an economically meaningful decomposition of the

MPI is equivalent to discard any proposal whose terms cannot be consistently interpreted in a theory of production context. In this respect, while (8), (11) and (12) decompose in terms which have a clear interpretation, we observe that some of them can be combined in different but intelligible ways to produce the same MPI result. However, by choosing any of the two latter decompositions one sacrifices some information regarding technical and scale changes, even if both proposals are interrelated. In fact, from (6) $PTC_G^{1,t}\left(x_i^t, y_i^t;\alpha\right)=TC_G^{1,t}\left(x_i^t, y_i^t;\alpha\right)\cdot STC_G^{1,t}\left(x_i^t, y_i^t;\alpha\right)$, and from (9) $SEC_G^1\left(x_i^1, y_i^1, x_i^t, y_i^t;\alpha\right) = RTS_G^1\left(x_i^1, y_i^1, x_i^t, y_i^t;\alpha\right) / STC_G^{1,t}\left(x_i^t, y_i^t;\alpha\right)$. Therefore, the scale—bias—of technical change $STC_G^{1,t}\left(x_i^t, y_i^t;\alpha\right)$ represents the cornerstone that links both decompositions, rendering possible a complete characterization of productivity change both from a technological—best practice—and efficiency perspective. Including this term in the MPI decomposition allows immediate access to all components that have been proposed in the literature.

As a result Zofío (2007) argues in favour of the enhanced decomposition (8) by SWLZ (1998) as it is the most comprehensive by considering all the terms in which previous proposals decompose and can be easily recovered from—*i.e.* it provides the "building blocks" of any decomposition found in the MPI literature with regards to the contribution that scale change makes to productivity change. Therefore if one wants to know the whole picture about the change in technology and efficiency, while assessing the role that productive scale plays in productivity change, choosing the enhanced decomposition would ease such task, since all terms are calculated or can be easily determined by simple computations. On these grounds, the extended decomposition (8) is the only one offering the whole picture about the contribution that technological change, technical efficiency change and scale —in its different definitions— make to productivity change. This means that opting for this decomposition of the MPI enriches the analysis, allowing a complete assessment of the general framework where productivity change takes place.

6. Empirical Implementation by Means of the Activity Analysis, DEA

In this section we illustrate how to undertake the MPI analysis that allows us to determine the sources of productivity growth within the SFTP. In doing so, we rely on the non-parametric Data Envelopment Analysis (DEA) techniques. This approach to efficiency and productivity measurement approximates the true but unknown technology by means of piecewise linear combinations of the observed data, which constitute a multidimensional production frontier –see Cooper, Seiford and Tone (2000) for an introduction to DEA within a production theory context. The DEA piecewise linear approximation of the technology –including its constant returns to scale characterization, is given by:

$$\hat{T}^t = \left\{(x,y): \sum_{i=1}^{I} z_i^t x_{in}^t \leq x_n^t,\ n=1,\ldots,N;\ \sum_{i=1}^{I} z_i^t y_{im}^t \geq y_m^t,\ m=1,\ldots,M;\ z_i^t \geq 0,\ i=1,\ldots,I\right\}, \tag{13}$$

where z^t is a intensity vector whose values determine the linear combinations or *facets* which define the production frontier.

Our first program deals with the empirical implementation of the generalized distance function $\mathrm{D}^t_{\mathrm{G}}(x^t, y^t; \alpha)$ representing technical efficiency. Specifically, to calculate this economic performance measure for any research unit *i'* we follow Zofio and Prieto (2006) and solve the following linear programming problem:

$$D^t_{\mathrm{G}}(x^t_{i'}, y^t_{i'}; \alpha) = \min_{\delta, z^t} \left\{\delta : (x^t_{i'}\delta^{1-\alpha}, y^t_{i'} / \delta^{\alpha}) \in \mathrm{T}^t\right\}$$

s.t.

$$\sum_{i=1}^{\mathrm{I}} \mathrm{z}^t_i \mathrm{x}_{in} \leq x^t_{i'n}\delta^{1-\alpha}, \quad n = 1,...,\mathrm{N},$$

$$\sum_{i=1}^{\mathrm{I}} \mathrm{z}^t_i \mathrm{y}_{im} \geq \mathrm{y}^t_{i'm} / \delta^{\alpha}, \quad m = 1,...,\mathrm{M},$$

$$\sum_{i=1}^{\mathrm{I}} \mathrm{z}^t_i = 1, \; z^t \in \Re^{\mathrm{I}}_{+},$$

(14)

while the constant returns to scale generalized distance function $\hat{D}^t_{\mathrm{G}}(x^t_i, y^t_i; \alpha)$—representing productive efficiency and comprising technical and scale efficiency—can be calculated solving for the same problem but dropping the convexity constraint $\Sigma^{\mathrm{I}}_{i=1} z^t_i = 1$. Therefore the scale efficiency term $\mathrm{SE}^t(x^t, y^t; \alpha) = \mathrm{PE}^t(x^t, y^t; \alpha) / \mathrm{TE}^t(x^t, y^t; \alpha) = \hat{D}^t_{\mathrm{G}}(x^t, y^t; \alpha) / D^t_{\mathrm{G}}(x^t, y^t; \alpha)$ is the result of dividing the solution obtained when solving (14) by its constant returns to scale counterpart.

Finally, the mix–period generalized productive efficiency of process *i'* observed in the comparison period with respect to the base period technology can be obtained by modifying (14) and solving for:

$$D^1_{\mathrm{G}}(x^t_{i'}, y^t_{i'}; \alpha) = \min_{\delta, z^0_i} \left\{\delta : (x^t_{i'}\delta^{1-\alpha}, y^t_{i'} / \delta^{\alpha}) \in \mathrm{T}^1\right\}$$

s.t.

$$\sum_{i=1}^{\mathrm{I}} \mathrm{z}^1_i \mathrm{x}^1_{in} \leq \mathrm{x}^t_{i'n}\delta^{1-\alpha}, \quad n = 1,...,\mathrm{N}, \qquad (15)$$

$$\sum_{i=1}^{\mathrm{I}} \mathrm{z}^1_i \mathrm{y}^1_{im} \geq \mathrm{y}^t_{i'm} / \delta^{\alpha}, \quad m = 1,...,\mathrm{M},$$

$$\sum_{i=1}^{\mathrm{I}} \mathrm{z}^1_i = 1, \quad z^1 \in \Re^{\mathrm{I}}_{+}.$$

As with previous case to calculate the constant returns to scale generalized functions representing mix period distance functions $\hat{D}^1_{\mathrm{G}}(x^t_{i'}, y^t_{i'}; \alpha)$ it is necessary to solve the same problems without the constraint $\Sigma^{\mathrm{I}}_{i=1} \mathrm{z}^t_i = 1$.

All these programs allow the empirical implementation of the proposed productivity change analysis, rendering possible to decompose the MPI into the alternative terms already described.

7. Empirical analysis

We constructed a data base including inputs and outputs provided to and generated by the research units participating in R&D projects financed by the SFTP between 1988 and 1999. As suggested by several researchers, we conduct our analysis at the micro level, *i.e.* we do not consider the host public research centers as the decision making unit, but only the various research groups[5] operating within them (Olazarán et al. 2004). Consequently, different research units operating in the same center can participate in the programme, and therefore are individually evaluated in our study. Our target Decision Making Units (DMUs) include research units receiving financial and human capital inputs from the Spanish Central Administration to promote applied research within the SFTP. From an institutional perspective they belong to the Spanish National Research Council (CSIC)[6]. The CSIC had been conducting research in food technology since the 1940s and had designed its own financial schemes to support applied research since the early 1980s[7]. Therefore, when the SFTP was introduced in 1988, the CSIC research centers in the food technology area were the only ones ready to apply for funding under this new scheme. This resulted in a large percentage of the financial support for R&D projects (up to 60%) being awarded to CSIC research units between 1988 and 1991 (I Spanish R&D Plan). This share dropped to 40% under the II Spanish R&D Plan (1992-1995) in favor of universities, and this proportion was maintained during the III R&D Plan (1996-1999). Due to the large proportion of R&D projects obtained by CSIC research groups, and the homogeneity of CSIC centers in terms of internal structure, institutional framework, research behavior and other contextual variables—most notably the absence of teaching duties—we have restricted our analysis to these types of research groups. By focusing on a smaller, but nevertheless homogenous and quite representative

[5] We define the research group as the set of researchers who participate together in research projects and this set remains unchanged from one project to another in at least ¾ of its members. Therefore a certain research group may evolve and decompose into (or merge with) new different research units according to our definition.
[6] The Spanish National Research Council (CSIC) is the largest PRI in Spain. In 2005 it was structured in 116 Centers, employing 2,364 scientists, 3,896 graduate and postgraduate researchers, and 4,084 support staff. Its budget was €700.8 million.
[7] The oldest CSIC center in this field is the Institute for Research in Industrial Ferments (IFI), which was created

set of research groups, we considered that the dynamic evaluation of the SFTP would provide more conclusive results.

Data were gathered from the central administration body responsible for the project management –*Dirección General de Enseñanza Superior e Investigación Científica*, and also responsible for collecting, processing and checking the final research statements submitted by research groups, which detail the outputs achieved within each R&D project financed by the programme. For the purposes of our study we focus on the role of R&D projects in terms of financial and human capital inputs and three categories of outputs jointly representing a multidimensional output mix, namely training (PhD dissertations and trained scientific personnel), science-technology outputs (international articles and patents), and socio-economic outputs (bilateral R&D contracts with firms).

With regard to the periodicity used in our study some explanation is needed. The time period under study, 1988-1999, comprises the first three Spanish R&D Plans—each covering a period of four years. However, we did not adopt a four year periodicity, as R&D projects within the SFTP may last up to three year (CICYT 1987; Jiménez-Sáez 2005). A successful research group that obtains funding every time it applies, i.e. every three years, thus overlapping R&D Plans, would chain four projects over the 12 year period—each of three years' duration. This applies to the more comprehensive and consolidated research groups. Hence, our analysis is split into four periods, covering the natural periodicity length of R&D projects: 1st period: 1988–1990; 2nd: 1991–1993; 3rd: 1994–1996; and 4th: 1997–1999. Table 1 summarizes the variables used in the analysis, classified by input and output categories, as well as their inter-periodical growth rate—first three columns—as well as over and the entire time span—last column.

Table 1.- Mean inter-periodical growth rates for inputs and outputs in the SFTP (%)

Variables/Period	1991-1993/ 1988-1990	1994-1996/ 1991-1993	1997-1999/ 1994-1996	1997-1999/ 1988-1990
Inputs				
Personnel	-17.5	-15.6	-42.5	-60.3
Public Funding	-24.2	-8.8	-11.9	-47.9
Outputs				

in 1939.

Training				
Trained people	-1.3	-0.2	82.8	51.3
PhD Theses	-30.0	-21. 1	-40.1	-66.9
Science & Technology				
International Papers	18.5	-5.8	-16.2	-23.1
Registered Patents	-83.3	-28.6	-42.5	-73.3
Socio-economic				
R&D Contracts	-23.1	500.3	480.0	137.6

Source: Own elaboration

Based on the number of research groups, both the number of personnel and overall budget devoted to the SFTP decline markedly from the first to the last period (1997-1999/1988-1990), as well as in consecutive periods. From an output perspective, there is a marked growth in the number of R&D contracts signed between research units and private firms to promote joint partnerships leading to practical innovations (137% when accounting for the change in the whole period). This remarkable increase suggests that the Spanish public research bodies are contributing extensively to the articulation of the SFIS (García-Martínez and Briz, 2000), which may be seen as the result of the efforts that research units make to raise more private funds to compensate for decreasing public funds. In terms of the output variables related to training, while the number of trained people shows a noticeable increase (51%) from 1988–1990 to 1997–1999, the number of doctoral theses decreases by 66%. The remaining variables representing S&T outputs, both number of international papers and registered patents show negative rates (–23% and –73% respectively). With decreasing input variables and increasing output variables—or decreasing to a lesser extent than the inputs, it is expected that research productivity growth is to be observed throughout the period.

7.1. Productivity change within the SFTP

Jiménez–Sáez et al. (2007) perform a period by period efficiency analysis using the same data set to test to what extent CSIC research units are able to make efficient use of these diminishing budgets, and whether their traditional mode I research behavior, based on the attainment of pure scientific-technological results, is changing towards mode II, which includes additional results that involve relationships with other agents, such as embedding personnel of firms within the units to train it, as well as bilateral R&D contracts with firms, representative both of actions contributing to the articulation of an IS. Therefore, besides individual efficiency rankings, they also aimed at testing whether the research units have been able to articulate the SFIS by adopting generalized strategies involving joint research initiatives with private firms. They carried out this research within the same DEA generalized distance function framework developed by Chavas and Cox (1999) as presented in equation (14), and therefore their results based on period by period efficiency analysis can be consistently recalled in this study, as they are fully compatible with the productivity change results presented in what follows—e.g. the efficiency change term $EC_G^{1,t}$ can be directly calculated by taking the ratio of the efficiency scores corresponding to successive years reported by Jiménez–Sáez et al. (2007: 23). Based on their results these authors propose a taxonomy of the efficient research units depending on their research strategies, which can be divided into: (i) comprehensive, (ii) partial, (iii) specialized and (iv) "shooting stars". Comprehensive groups perform an efficient multidimensional research strategy by producing all outputs and have an in depth knowledge of the SFIS. Partial research units represent the largest group comprising those observations whose activities are directed towards the two output dimensions that characterize scientific knowledge production in mode I, i.e. training and S&T variables. Specialized groups are those research units that are consistently efficient by focusing on either S&T variables or socio-economic goals related to profitable bilateral contracts with interest in particular research actions. Finally, "shooting stars" describes those efficient research units that sporadically participate in the SFTP with the objective of achieving a particular goal (i.e. accomplishing a specific project, signing a bilateral contract with a firm, etc.), but are not able to raise funds within the SFTP consistently in more than one period[8]. Bearing in mind this typology we study from a dynamic perspective overall productivity growth, examine the sources contributing to its increase as shown in sections 5 and 6, and highlight the most relevant trends followed by the alternative groups.

The mean growth rates for all periods of the cumulated MPI are presented in Table 2, sorted by their (in)efficiency status and group typology: comprehensive, partial and specialized (values for

[8] As a result it is not possible to study productivity change for these efficient units, as well as any other inefficient unit participating in the SFTP in a single period.

the individual units are reported in annex 1)[9]. Calculating average inter–periodical productivity growth rates is necessary so as to render comparable the productivity change of units participating in different number of periods, i.e. not all the CSIC research units included in the analysis participate in the four sub-periods comprising the whole time length under study.

The alternative decompositions are presented starting with the FGNZ proposal, easing a top-down discussion of the different terms in which the MPI can be decomposed.

Table 2.- Average inter-periodical cumulated productivity change by groups

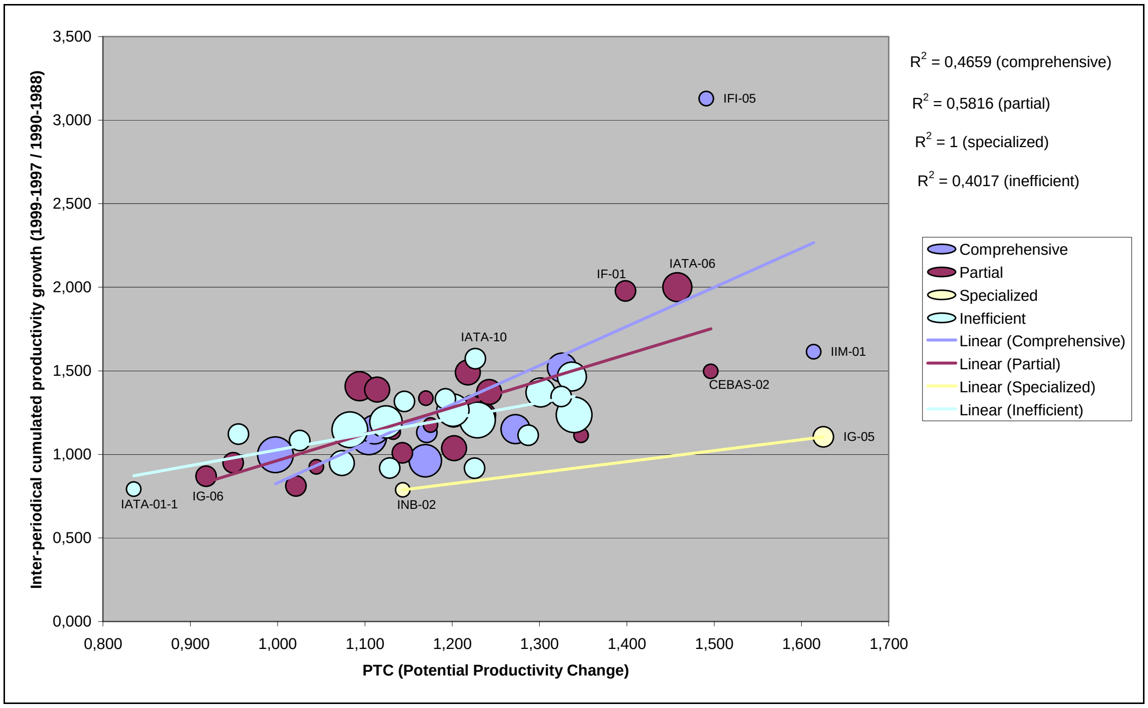
		FGNZ			**RD**			**SWLZ**			
	$M_G^{1,t}$	$PTC_G^{1,t}$	$TEC_G^{1,t}$	$SEC_G^{1,t}$	$TC_G^{1,t}$	$TEC_G^{1,t}$	$RTS_G^{1,t}$	$TC_G^{1,t}$	$STC_G^{1,t}$	$TEC_G^{1,t}$	$SEC_G^{1,t}$
All R.U.											
Mean	1.193	1.155	1.017	1.009	1.235	1.017	0.957	1.235	0.953	1.017	1.009
St. Dev.	0.347	0.167	0.137	0.102	0.282	0.137	0.105	0.282	0.102	0.137	0.102
Max	3.130	1.625	1.414	1.566	2.420	1.414	1.242	2.420	1.213	1.414	1.566
Min	0.787	0.835	0.680	0.739	0.824	0.680	0.631	0.824	0.616	0.680	0.739
All Efficient R.U.											
Mean	1.282	1.215	1.022	1.015	1.351	1.022	0.928	1.351	0.920	1.022	1.015
St. Dev.	0.444	0.177	0.157	0.118	0.319	0.157	0.108	0.319	0.118	0.157	0.118
Max	3.130	1.625	1.414	1.566	2.420	1.414	1.070	2.420	1.087	1.414	1.566
Min	0.787	0.918	0.680	0.763	0.955	0.680	0.650	0.955	0.616	0.680	0.763
— Compreh. R.U.											
Mean	1.417	1.251	1.028	1.057	1.430	1.028	0.948	1.430	1.028	1.057	0.916
St. Dev.	0.679	0.198	0.127	0.197	0.460	0.127	0.118	0.460	0.127	0.197	0.169
Max	3.130	1.614	1.340	1.566	2.420	1.340	1.048	2.420	1.340	1.566	1.087
Min	0.679	0.198	0.127	0.197	0.460	0.127	0.118	0.460	0.127	0.197	0.169
— Partial R.U.											
Mean	1.256	1.184	1.041	1.010	1.316	1.041	0.922	1.316	0.912	1.041	1.010
St. Dev.	0.314	0.151	0.157	0.044	0.248	0.157	0.107	0.248	0.095	0.157	0.044
Max	2.000	1.496	1.414	1.142	2.039	1.414	1.070	2.039	1.021	1.414	1.142
Min	0.810	0.918	0.829	0.919	0.955	0.829	0.690	0.955	0.690	0.829	0.919
— Specialized R.U.											
Mean	0.946	1.384	0.791	0.881	1.364	0.791	0.897	1.364	0.791	0.881	1.022
St. Dev.	0.224	0.341	0.158	0.167	0.403	0.158	0.125	0.403	0.158	0.167	0.052
Max	1.104	1.625	0.903	1.000	1.649	0.903	0.985	1.649	0.903	1.000	1.059
Min	0.787	1.143	0.680	0.763	1.080	0.680	0.808	1.080	0.680	0.763	0.986
All Inefficient R.U.											
Mean	1.186	1.169	1.021	1.003	1.212	1.021	0.975	1.212	0.974	1.021	1.003
St. Dev.	0.205	0.138	0.155	0.114	0.193	0.155	0.126	0.193	0.093	0.155	0.114
Max	1.573	1.340	1.295	1.216	1.569	1.295	1.242	1.569	1.213	1.295	1.216
Min	0.792	0.835	0.729	0.739	0.824	0.729	0.631	0.824	0.819	0.729	0.739

Note: We report mean values for all units classified within the group—see Annex 1 for individual values.
Source: Own elaboration

[9] Note that in Table 2 we present mean values of the Malmquist indices and the different terms in which it decomposes; therefore, multiplying the values reported in Table 2 will not normally result in their aggregates. However, this multiplicative nature of the Malmquist index and its components is preserved in annex 1, where all terms can be obtained by direct multiplication.

Malmquist productivity change within the SFTP increased inter–periodically by 19.3% = (1.193-1)*100, with efficient units exceeding their inefficient counterparts by 51.6%. The main driver of productivity growth is the change in the technology led by the efficient units operating at the most productive scale sizes, MPSSs—eq. (6), since potential technical change $PTC_{G}^{1,t}$—i.e. the upward shift in the production frontier at the technical and scale efficient *loci*, presents a 15.5% annual increase. Decomposing $PTC_{G}^{1,t}$ into its two sources, it is the shift in the production frontier allowing for variable returns to scale $TC_{G}^{1,t}$ what brings higher gains, 23.5%—this measure can be interpreted as the frontier shift for the average output-input scales corresponding to each group. The remaining term, $STC_{G}^{1,t}$ shows that productivity change at those average output–input scales exceeds that observed at the MPSSs by 4,7%, and therefore technical change presents a bias in favour of the average productive scale when compared to that observed at the optimal ones. Productivity growth is barely boosted by efficiency change, $EC_{G}^{1,t} = TEC_{G}^{1,t} \cdot SEC_{G}^{1,t}$—eq. (5)—as it contributes with a meager 2.6% increase, i.e. 1.026 = 1.017 · 1.009. Furthermore, technical change $TEC_{G}^{1,t}$ at the mean output–inputs scales amounts 1.7% per year, while $SEC_{G}^{1,t}$ stays at 0.9%. From these results we conclude that, in relative terms, there is not a relevant and generalized catch–up process within the SFTP according to which inefficient research groups would converge toward the efficient frontier by adopting the best practice research strategies and behavior of the leading units, resulting in a slow rate of convergence. This is consistent with the results reported by Jimenez–Saéz et al (2007: 23-24) showing mean efficiency scores, whose values remain unchanged around 75% in the four considered periods. Finally, the last source of productivity growth corresponding to the contribution that returns to scale $RTS_{G}^{1,t}$ shows that changes in the output–input size carry decreasing returns to scale resulting in productivity decline. We remark that the relative contribution of these terms to productivity change is similar across all groups of research units, either efficient or inefficient, as well as when sorting the former according to the previously discussed categories, i.e. as previously discussed the major source of productivity growth corresponds in every group to $PTC_{G}^{1,t}$ and, particularly, $TC_{G}^{1,t}$, while scale changes play a very limited role. As virtually all productivity growth is attributable to potential technical change, we depict in figure 1 the connection between these two measures for each individual research group classified according to efficiency status—inefficient and efficient (sorted by group category), and whose size is proportional to the average of funding throughout the four periods. The correlation coefficient for the most comprehensive units 0.47 is clearly influenced by IFI-05 that exhibits a Malmquist index of 3.130, and would be statistically significant and rather high, 0.760 if this particular unit were excluded.[10]

Figure 1.- Distribution of average inter-periodical cumulated change in $PTC_G^{1,t}$ and $M_G^{1,t}$ by efficiency status and size



We focus now on the distribution of the inter-periodical cumulated productivity growth. Table

[10] However, anticipating our discussion on individual leading units, we stress that the remarkable productivity change value of IFI-05 cannot be recognized as an outlier resulting from data measurement errors, but as the outcome of an outstanding performance. This unit is able to increase outputs while reducing inputs resulting in a productivity growth $M_G^{1,t}$ =3.130 that can be mostly explained in terms of a remarkable technical change process at this unit's input-output scale is $TC_G^{1,t}$ =2.420, jointly with a substantial catching-up process equal to $TEC_G^{1,t}$ =1.340.

3 presents the Malmquist values for selected ranges—see figure 1. There we observe that just 10 research units exceed a 40% increase in productivity growth (20% of all units participating in the SFTP), while the bulk of the research units, 29, present productivity growths under 40% (58%). Interestingly, 11 research units (the remaining 22%) experience productivity decreases, mainly as a result of losses in technical and scale efficiency, whose average values decrease by -9.8% and -3.9% respectively, as the average potential productivity change available to them increases by 4.6%. Looking at the different terms contributing to productivity growth we observe that for the whole group of units attaining productivity change over 20%, all terms make a positive contribution to productivity growth —recall that $STC_G^{1,t} < 1$ has a positive interpretation, since it implies that the most productive scales converge in size to the mean output–input scale of the comparison units, therefore presenting a bias in favour of those grouped in each productivity range.

Table 3.- Distribution of the average inter–periodical cumulated productivity growth.

		FGNZ			RD			SWLZ			
	$M_G^{1,t}$	$PTC_G^{1,t}$	$TEC_G^{1,t}$	$SEC_G^{1,t}$	$TC_G^{1,t}$	$TEC_G^{1,t}$	$RTS_G^{1,t}$	$TC_G^{1,t}$	$STC_G^{1,t}$	$TEC_G^{1,t}$	$SEC_G^{1,t}$
$M_G^{1,t}$ > 40%; #R.U. = 10											
Mean	1,767	1,366	1,180	1,090	1,578	1,180	0,956	1,578	1,180	1,090	0,892
St. Dev.	0,522	0,157	0,155	0,183	0,391	0,155	0,095	0,391	0,155	0,183	0,131
Max	3,130	1,614	1,414	1,566	2,420	1,414	1,055	2,420	1,414	1,566	1,030
20% < $M_G^{1,t}$ < 40%; #R.U. = 13											
Mean	1.302	1.225	1.063	1.011	1.316	1.063	0.949	1.316	0.937	1.063	1.011
St. Dev.	0.061	0.067	0.093	0.111	0.133	0.093	0.144	0.133	0.079	0.093	0.111
0% < $M_G^{1,t}$ < 20%; #R.U. = 16											
Mean	1.118	1.178	0.971	0.996	1.271	0.971	0.939	1.271	0.946	0.971	0.996
St. Dev.	0.046	0.154	0.141	0.059	0.250	0.141	0.122	0.250	0.135	0.141	0.059
$M_G^{1,t}$ < 0%; #R.U. = 11											
Mean	0.898	1.046	0.902	0.961	1.075	0.902	0.938	1.075	0.977	0.902	0.961
St. Dev.	0.072	0.117	0.091	0.076	0.120	0.091	0.101	0.120	0.085	0.091	0.076
Min	0.787	0.835	0.729	0.763	0.824	0.729	0.694	0.824	0.755	0.729	0.763

Source: Own elaboration

7.2. Comparing productivity trends across efficient groups.

So far we have discussed the productivity trends of research units from a general perspective and focusing on their (in)efficiency status, as well as the their main drivers according to the alternative decompositions. However, more insight on best research practices can be gained by comparing the mean values of the MPI and its components across the different categories of efficient research units—Table 2. The units leading productivity growth are the comprehensive ones with an outstanding 41.7% increase, followed by units ascribed to the partial groups (25.6%), while units adopting a specialized research strategy in the output dimension exhibit some productivity decline (20.3%). These are important results suggesting that pursuing a comprehensive research activity results in higher productivity growth than relying on a specialized strategy focused on single and very specific activities such as patents and publications (S&T outputs) or bilateral joint ventures with private firms (R&D contracts). The rationale for this differential can be found in inter-product complementarities, and it can be argued that the usual reasons behind the existence of economies of scope, associated to common and shareable inputs in the production of joint multilateral outputs—already found by Koshal and Koshal (1999) in higher education, are present in research activities within the SFIS. This is particularly relevant from a policy oriented perspective since as argued by Jiménez–Saez et al. (2007), the burden of the articulation of the SFIS finally rests upon the comprehensive units, and therefore provides evidence supporting funding strategies that favour units adopting a holistic research vision.

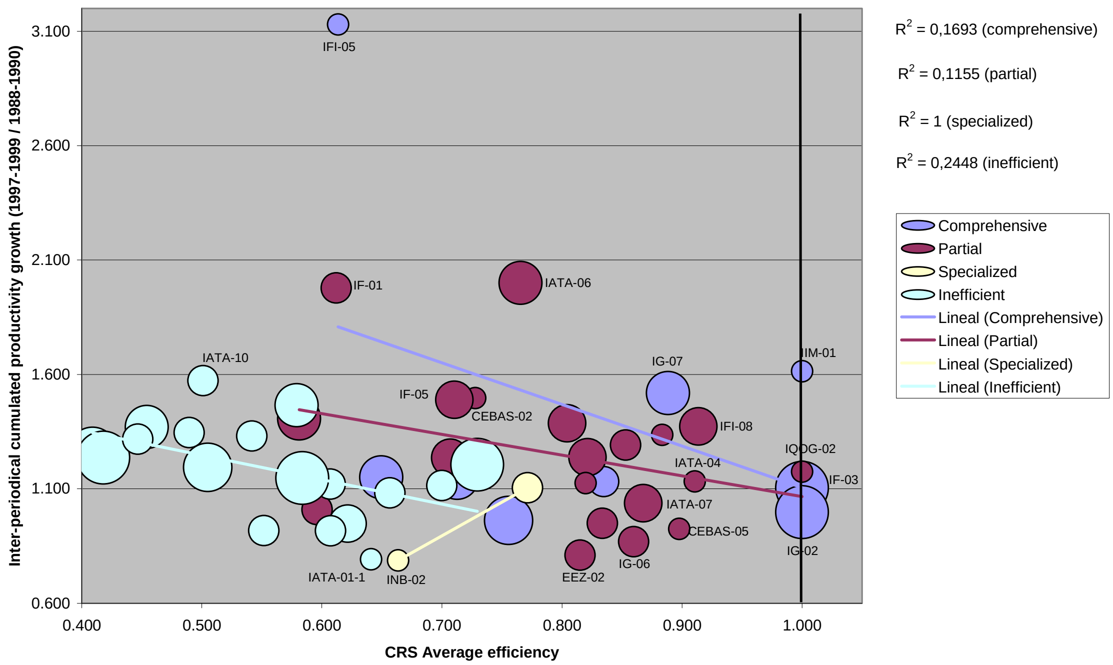
We conclude then that on average comprehensive research units producing a balanced output mix without neglecting any of the research dimensions (training, S&T and socio-economic) achieve higher productivity increases than their smaller specialized counterparts focusing on the production of a single output dimension –normally S&T outputs or R&D contracts–. Moreover, focusing in the FGNZ decomposition, we note that the mean value of potential productivity change $PTC_{G}^{1,t}$ for the comprehensive group (22.1%) exceeds that for all research units (15.5%) as well as the efficient units (21.5%), confirming that these units drive the production frontier upwards, and therefore increase maximum productivity at the most productive optimal scales in a remarkable value. Additionally, as the research units classified in the efficient groups are those that define the production frontier in at least one period, efficiency increases or decreases cannot be large in magnitude —when they are efficient in all periods from a technical and scale perspective (IG-02, IF-03, IQOG-02 and IIM-01 in our study). Then $EC_{G}^{1,t} = TEC_{G}^{1,t} \cdot SEC_{G}^{1,t} = 1$, and productivity growth cannot have origin in the catching-up process associated to efficiency increases[11]. This is illustrated in Figure 2 showing the relationship between the mean efficiency achieved by each research unit and its inter-periodical productivity change. It can be observed that the four units fully efficient in all periods do not manage to achieve high levels of productivity growth as they cannot benefit from efficiency improvements. This is a logical conclusion, as these units are the main responsible for the expansion of the benchmark production frontier[12]. Hence, if these units achieved higher levels of productivity change it would imply that the technological frontier is moving away rather rapidly, with the consequent loss of competitiveness for the remaining research units that would lag behind in their productivity change resulting in efficiency decreases. Zofío (2007: 2375) shows that the efficiency change experienced by a particular unit can be expressed as the ratio between its productivity change—Malmquist index—and the potential productivity change of the fully efficient leading units, i.e. how a unit's productivity change compares to those of the benchmark units: $EC_{G}^{1,t} = TEC_{G}^{1,t} \cdot SEC_{G}^{1,t} = M_{G}^{1,t} / PTC_{G}^{1,t}$. Therefore when $M_{G}^{1,t} < PTC_{G}^{1,t}$, $EC_{G}^{1,t} < 1$, implying that since the evaluated unit is not able to follow the productivity increases of the best research units, it lags behind losing efficiency. Finally, figure 2 portraits one of the main conclusions of our research: fully efficient comprehensive units of a relatively large size lead potential productivity growth rates, while large units with a partial research orientation tend to be very inefficient and therefore cannot lead the expansion of the production frontier.

Figure 2.- Distribution of cumulated inter-periodical change in $M_{G}^{1,t}$ and mean efficiency[13]

[11] As we present in Table 1 the values associated to the Malmquist index satisfying the circularity test and referred to first base period, all it is required for $EC_{G}^{1,t} = TEC_{G}^{1,t} \cdot SEC_{G}^{1,t} = 1$ in annex 1 is that research units are efficient in the base (1) and last periods, regardless of their efficiency level in the in-between periods.

[12] Notice that potential productivity change does not have to be led by a single research unit as it is just the change in maximum productivity between two periods—those attained at the optimal scales in each period, which may be achieved by different units in each period.

[13] The efficiency value is measured as the mean efficiency obtained by the research unit in the periods in which it has participated in the SFTP, while productivity change corresponds to the inter-periodical variation rate reported in Table 2, which as previously discussed also render comparable the values of the units participating in different number of periods. In this sense, the vertical line measures the mean efficiency (measured in constant returns to scale) achieved by all research groups in the four periods (0.691).



7.3. Productivity trends between periods

We now discuss productivity growth trends between periods. To ease the interpretation we recall the formulation of the fixed-base adjacent period version of the MPI (3) that can be decomposed in the same way as the MPI version relying on a constant reference period (4). Table 4 shows mean values of productivity change by group categories. For all research units we observe that productivity grows at a steady rate over the four periods, with a slight decreasing trend in the Malmquist index from 80.9% between the first two periods to 54.8% between the last two. However, looking at FGNZ's decomposition we observe that the relative contributions corresponding to potential productivity change $PTC^{1,t}_{G}$, and efficiency change $EC^{1,t}_{G} = TEC^{1,t}_{G} \cdot SEC^{1,t}_{G}$, greatly change across periods. While $PTC^{1,t}_{G}$ is the main source of productivity change between the first three periods, $TEC^{1,t}_{G}$ takes over between the last two, confirmed by the fact that productivity change at the most productive scale sizes comes to a sudden halt: $PTC^{1,t}_{G} = 1.090$, which favours a catching up process where the follower inefficient units are able to converge toward the frontier by reducing their relative technical inefficiency, $TEC^{1,t}_{G} = 1.584$, even if they are not able to approach the scale size of the most productive leading units, $SEC^{1,t}_{G} = 0.982$. This is an expected result since the size of research units in terms of inputs (personnel and funding) and outputs (training, S&T and socio-economic) remain stable over time —the mean value of these variables per research unit is unchanged over the four periods, except for bilateral contracts that triple in value, as shown by Jimenez–Saez et al. (2007: 22). This implies that the alternative decompositions by RD and SWLZ exploring the role that returns to scale $RTS_{G}^{1,t}$ and the scale bias of technical change $STC_{G}^{1,t}$ play in productivity change, also present the same relative small effects. Nevertheless we stress that scale efficiency improves between the second and third period by 15.1%, since changes in the individual input and output sizes carry increasing returns to scale with respect to the reference optimal sizes, enhanced by the fact that the latter also change in favour of the research units —as argued when discussing $SEC_{G}^{1,t} = RTS_{G}^{1,t} / STC_{G}^{1,t}$ in section 5.

We complete this discussion on productivity trends by stating that this overall general description of productivity change for all research units is consistent with the opposing time patterns of the efficient and inefficient groups. This means that when efficient units exhibit large technical change values, it is expected that inefficient units suffer from inefficiency increases as they are not able to keep up with their leading peers and therefore lag behind, e.g. between the second and third periods mean technical change $TC_{G}^{1,t}$ in the efficient group increases by 115.3%, and efficiency reduces by 29.3% in the inefficient group. But from the third to the fourth period the contrary takes place: as efficient units push the frontier to a lesser extent, 43.8%, this offers the possibility for the inefficient units to catch up, and mean technical efficiency increases by 115.4% in this group. Therefore, the lower the potential productivity change (productivity growth) driven by the leading units, the larger the efficiency change (catch-up) term. Finally we note that among the different groups of efficient units, there is some heterogeneity, with comprehensive and specialized units leading productivity change between the first and second periods, as well as between the third and fourth periods, while partial units take the lead between the second and third periods —with all the remaining terms behaving accordingly.

Table 4.- Productivity change between periods by group categories, Eq. (3)

	FGNZ	RD	SWLZ

	$M_G^{1,t}$	$PTC_G^{1,t}$	$TEC_G^{1,t}$	$SEC_G^{1,t}$	$TC_G^{1,t}$	$TEC_G^{1,t}$	$RTS_G^{1,t}$	$TC_G^{1,t}$	$STC_G^{1,t}$	$TEC_G^{1,t}$	$SEC_G^{1,t}$
All R.U.											
1988-90/91-93	1.809	1.496	1.115	1.023	1.596	1.115	0.993	1.596	1.019	1.115	1.023
1991-93/94-96	1.641	1.678	0.863	1.151	1.952	0.863	1.020	1.952	0.936	0.863	1.151
1994-96/97-99	1.548	1.090	1.584	0.982	1.438	1.584	0.880	1.438	0.915	1.584	0.982
All Efficient R.U.											
1988-90/91-93	1.883	1.549	1.081	1.010	1.758	1.081	0.911	1.758	0.969	1.081	1.010
1991-93/94-96	2.043	1.812	0.951	1.177	2.153	0.951	1.026	2.153	0.921	0.951	1.177
1994-96/97-99	1.548	1.090	1.584	0.982	1.438	1.584	0.880	1.438	0.915	1.584	0.982
— Compreh. R.U.											
1988-90/91-93	2.803	1.755	1.151	1.189	2.287	1.151	0.962	2.287	0.887	1.151	1.189
1991-93/94-96	1.192	1.159	1.030	1.013	1.139	1.030	1.011	1.139	1.018	1.030	1.013
1994-96/97-99	0.938	1.056	0.971	0.951	1.242	0.971	0.862	1.242	0.930	0.971	0.951
— Partial. R.U.											
1988-90/91-93	1.257	1.337	1.044	0.901	1.355	1.044	0.875	1.355	1.020	1.044	0.901
1991-93/94-96	2.459	2.077	0.955	1.250	2.577	0.955	1.034	2.577	0.880	0.955	1.250
1994-96/97-99	1.710	1.055	1.465	1.013	1.434	1.465	0.954	1.434	0.942	1.465	1.013
— Specialized R.U.											
1988-90/91-93	2.662	2.662	1.000	1.000	2.765	1.000	0.963	2.765	0.963	1.000	1.000
1991-93/94-96	0.506	1.613	0.314	0.999	1.622	0.314	0.993	1.622	0.994	0.314	0.999
1994-96/97-99	-	-	-	-	-	-	-	-	-	-	-
Inefficient R.U.											
1988-90/91-93	1.646	1.381	1.190	1.050	1.240	1.190	1.176	1.240	1.129	1.190	1.050
1991-93/94-96	0.895	1.429	0.702	1.104	1.578	0.702	1.010	1.578	0.964	0.702	1.104
1994-96/97-99	1.780	1.157	2.154	0.968	1.578	2.154	0.802	1.578	0.870	2.154	0.968

Note: the different indices are based on the first period (1988-90) and the consecutive periods correspond to the following years: 1, *t*: 1988-90/91-93; *t*, *t*+1: 1991-93/94-96, and *t*+1, *t*+2: 1994-96/97-99
Source: Own elaboration

7.4. Productivity trends of leading research units

To identify best practice behavior in research productivity we discuss in depth the productivity trends of the leading units achieving remarkable average inter-periodical productivity growths over 50%. In Annex 1 we find that among the efficient units, that achieving the highest growth is IFI-05 (212.0%), categorized as comprehensive, followed by IATA-06 (specialized in S&T) that reaches a 100.0%, IF-01 (partially oriented in training and S&T) with a 97.8% rate and, finally, IIM-01 (also categorized as comprehensive) that presents a 61.4% productivity increase. IFI-05 participated in the first two periods under study (1988-90 and 1991-93), and the main reasons for its leading productivity growth is the observed increase in the number of publications (no papers in the first period and 4 in the second), along with the enlargement observed in the bilateral R&D contracts with private firms (from 5.787€ to 12.380€, respectively), and a reduction of 72.1% in the public funding obtained from the SFTP (45.397€ in the first period and 13.222€ in the second). Despite its small size, it is remarkable how this unit managed to evolve from an inefficient specialized unit in the first period to an efficient comprehensive unit in the second period. In this scheme the potential for productivity growth is enormous because IFI-05 can ripe the benefits of the technological change driven by the leading units, while being able to catch–up with the frontier, i.e. $M_G^{1,t} > PTC_G^{1,t}$ and therefore $EC_G^{1,t} > 1$ —Figure 2 presenting the relationship between mean efficiency and productivity change allow us to see the extent for potential efficiency improvements. Regrettably, this unit was not able to survive as a result of its rather small size, when compared to other comprehensive units leading productivity research in absolute terms. Contrarily to IFI-05, IATA-06 participated in the last two periods, being a specialized research group whose productivity growth is mainly due to the decreasing amount of inputs employed as the production of outputs was constant in time. This input trend is also observed for IF-01 that participated in the SFTP in all four periods. It is considered as a partial research group because its outputs are mainly oriented towards producing training and S&T results (publications and patents). The reason behind its remarkable productivity growth is the extreme reduction in the public funding obtained from the SFTP (from 81.557€ in 1988 to 15.025€ in 1997) as output production remains constant. As regards the story behind IIM-01, we note that this research unit participated intermittently in the first, second and fourth periods. On the input side it reduced the personnel devoted to participating in the SFTP from 3 full time equivalent personnel in the first period to 1 in the last period, while the funding awarded by the SFTP was also reduced from 85.283€ to 55.052€ respectively. On the output side IIM-01 doubled from 3 to 6 the people in training, and what is more spectacular, elevated from null to 120.064€ the funding obtained from private R&D contracts with firms. As a setback, the number of publications fell from 12 to 5 over these years. From this discussion we clearly conclude that productivity increases are driven by very different trends in inputs and outputs variations. Even if what counts in the end for productivity growth is that output change must be larger than input change, it can be shown that in many cases this relative growth is result of declining inputs trends rather that output increases. A situation that concerns R&D managers since the goals of the programme—as stated in section 3—were to encourage scientific research, training as well as technological innovation and transfer, and this contribution to output growth is not always granted by remarkable productivity increases.

8. Conclusions

The SFTP, as other R&D Programmes within the Spanish R&D plan—which is comparable to similar plans in developed countries, was designed to cover all the stages in the innovation process, offering possibilities for participation to a wide variety of agents, and fostering co-operation among them. Our goal is to propose an evaluation Framework that allow R&D managers to assess the efficiency and productivity performance of research units participating in a particular technology and innovation programme.

We believe that our study of the characteristics of research units exhibiting a best practice behaviour associated to high productivity levels shows the potential of the proposed Malmquist productivity change analysis as a valid methodology to undertake research performance evaluations. We draw several practical conclusions that may constitute guidelines for research managers, and make the following policy recommendations:

i) Overall the Spanish SFTP has exhibited an outstanding inter–periodical productivity growth with an average 19.3% increase every three years —around 6% yearly, showing that the allocation of inputs by the SFTP has been successful in general. However, this trend is not observed to the same extend across research units since our analysis unveils a high heterogeneity that can be discussed according to the topology identified by Jiménez–Saez et. al (2007): comprehensive, partial and specialized research units.

ii) Groups undertaking a comprehensive research should be promoted by the programme as they prove themselves not only efficient in managing the scarce resources made available to them, but also capable of fostering research productivity growth while increasing their multidimensional output. Over the twelve year period this group increased its productivity by 41,7% on average, outgrowing the productivity rates of other groups of efficient units that, despite being more numerous, do not contribute to the same extent to the achievement of the goals of the SFTP because of their partial or specialized research orientation—these units in particular exhibit a productivity decline to the tune of –5,5%). Moreover, since comprehensive units rank high in terms of their efficiency levels (some of them being always efficient throughout the whole period) we confirm that the main source of this remarkable productivity growth is the expansion of the research frontier—potential productivity change.

iii) Managers should be worried about the fact that the higher share of the units adopt a partial research orientation, focusing their work solely on science and technology outputs (mainly articles published in international journals), rather than undertaking personnel training or signing bilateral R&D contracts with the private sector. The reason behind this narrow research orientation is that the promotion of their members is based by far on this criterion. This is particularly grave since most of the inefficient units follow this partially oriented research strategy. This suggests that the incentives of academics do not agree with those of R&D managers, and that research activities that contribute to a larger extent to the articulation of the Spanish Food Innovation System are prone to principal-agent problems that result in inefficient research practices.

iii) Looking at the average evolution in productivity growth for those units participating in the SFTP that start out from an inefficient situation, ours results confirm that they are not able to converge toward the production frontier, casting a shadow on their performance. On average they are able to attain productivity growth levels that barely match those of their efficient counterparts. This is rather unsatisfactory from a policy evaluation perspective because it implies that they are not able to profit from a catching–up process thereby reducing average inefficiency within the SFTP. One the reasons why inefficiency levels remain constant over the period is that inefficient units are not able to converge toward the optimal production scale represented by the comprehensive units, whose size in terms of the amount of output and inputs is well above the average.

iv) The analysis shows that large units undertaking a comprehensive research must constitute the benchmark peers against which all remaining units are confronted, and therefore their best practices should become the guidelines underlying the financial scheme of the program. Based on this conclusion we believe that a new financial line introduced in the announcement of the 2006 Spanish R&D plan (including the SFTP), reorienting some of the funding so as to promote the creation and consolidation of this kind of units, must be welcomed. The new line, known as “consolider”, extends the duration of the average project form 3 to 5 years and grants an average budget of 1 million Euros. Nevertheless, to apply to this line, a minimum size must be met, *i.e.*, it is required that a minimum of 5 units—with at least 4 researchers each—agree on a single proposal. Besides the general objectives of all programs, the declared goal of this line is to increase the competitiveness of Spanish research groups at international levels, *e.g.* the seventh European framework program (FP7), by increasing the “critical mass” of research groups—i.e. creating large comprehensive units— that should translate into higher the research productivity.[14] In a sense this change in the R&D Plans acknowledges the pitfalls of the financial scheme existing until then. Since grants could not be awarded to large groups because there was not a particular financial line specifically aimed at promoting the consolidation of larger groups, most of the funding would end up in units carrying out a partial research orientation, whose

[14] In this year research proposals were evaluated using different criteria depending on their characteristics: i) the “consolider” line already described, ii) the general and conventional line that did not require a minimum size (i.e. using the criteria exiting until then) and iii) a line reserved to young researchers under 40 years old and whose proposal clearly departs from those of their supervisors. This segmentation of the financial scheme system guarantees that funds are allocated among researchers competing in the same category, as using one single set of criteria did not give managers the flexibility to finance large projects on a long term basis or ensure that enough fund would reach young researchers. In a sense these changes in the R&D Plans acknowledged the pitfalls of the financial scheme existing until then. Since grants could not be awarded to large groups because there was not a particular line specifically aimed at promoting the consolidation of larger groups, most of the funding would end up in units carrying out a partial research orientation, whose results have been less satisfactory as already discussed.

results are less satisfactory on average as already discussed.

Annex 1. Average inter-periodical cumulated productivity change for individual units.

		FGNZ			RD			SWLZ			
	$M_G^{1,t}$	$PTC_G^{1,t}$	$TEC_G^{1,t}$	$SEC_G^{1,t}$	$TC_G^{1,t}$	$TEC_G^{1,t}$	$RTS_G^{1,t}$	$TC_G^{1,t}$	$STC_G^{1,t}$	$TEC_G^{1,t}$	$SEC_G^{1,t}$
CEBAS-01	1.291	1.222	1.050	1.006	1.387	1.050	0.886	1.387	0.881	1.050	1.006
CEBAS-02	1.496	1.496	1.000	1.000	1.517	1.000	0.986	1.517	0.986	1.000	1.000
CEBAS-03	1.336	1.170	1.000	1.142	1.329	1.000	1.005	1.329	0.880	1.000	1.142
CEBAS-04	1.331	1.192	1.115	1.000	1.225	1.115	0.974	1.225	0.973	1.115	1.000
CEBAS-05	0.924	1.044	0.890	0.995	1.057	0.890	0.983	1.057	0.988	0.890	0.995
CID-01	1.264	1.201	0.868	1.212	1.171	0.868	1.242	1.171	1.025	0.868	1.212
EEZ-02	0.810	1.021	0.829	0.957	1.089	0.829	0.897	1.089	0.938	0.829	0.957
IATA-01	1.205	1.229	1.000	0.981	1.500	1.000	0.803	1.500	0.819	1.000	0.981
IATA-01-1	0.792	0.835	0.951	0.997	0.824	0.951	1.010	0.824	1.013	0.951	0.997
IATA-02	0.962	1.169	0.908	0.906	1.075	0.908	0.985	1.075	1.087	0.908	0.906
IATA-03	1.236	1.236	1.000	1.000	1.241	1.000	0.996	1.241	0.996	1.000	1.000
IATA-04	1.133	1.133	1.000	1.000	1.198	1.000	0.945	1.198	0.945	1.000	1.000
IATA-05	0.947	1.074	0.884	0.998	1.064	0.884	1.007	1.064	1.009	0.884	0.998
IATA-06	2.000	1.458	1.363	1.007	2.039	1.363	0.720	2.039	0.715	1.363	1.007
IATA-07	1.037	1.202	0.882	0.978	1.177	0.882	0.999	1.177	1.021	0.882	0.978
IATA-08	1.009	1.143	0.884	0.999	1.262	0.884	0.904	1.262	0.906	0.884	0.999
IATA-09	1.370	1.301	1.083	0.972	1.260	1.083	1.004	1.260	1.033	1.083	0.972
IATA-10	1.573	1.227	1.055	1.216	1.414	1.055	1.055	1.414	0.868	1.055	1.216
IATA-11	0.918	1.128	0.803	1.013	1.170	0.803	0.977	1.170	0.964	0.803	1.013
IF-01	1.978	1.398	1.414	1.000	1.497	1.414	0.934	1.497	0.934	1.414	1.000
IF-02	1.113	1.348	0.832	0.992	1.553	0.832	0.861	1.553	0.868	0.832	0.992
IF-03	1.105	1.105	1.000	1.000	1.699	1.000	0.650	1.699	0.650	1.000	1.000
IF-03-1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
IF-04	1.148	1.111	1.056	0.978	1.066	1.056	1.019	1.066	1.042	1.056	0.978
IF-05	1.489	1.218	1.210	1.011	1.220	1.210	1.009	1.220	0.998	1.210	1.011
IF-06	0.917	1.226	0.729	1.026	1.262	0.729	0.996	1.262	0.971	0.729	1.026
IF-07	1.082	1.025	1.063	0.993	1.197	1.063	0.851	1.197	0.857	1.063	0.993
IF-08	1.466	1.337	1.153	0.951	1.298	1.153	0.979	1.298	1.030	1.153	0.951
IF-09	1.121	0.955	1.162	1.009	0.933	1.162	1.033	0.933	1.024	1.162	1.009
IFI-01	1.407	1.094	1.216	1.057	1.212	1.216	0.955	1.212	0.903	1.216	1.057
IFI-02	1.147	1.083	0.948	1.117	1.105	0.948	1.095	1.105	0.980	0.948	1.117
IQOG-01	1.193	1.124	1.295	0.820	0.927	1.295	0.994	0.927	1.213	1.295	0.820
IFI-03	1.236	1.340	1.249	0.739	1.569	1.249	0.631	1.569	0.854	1.249	0.739
IFI-05	3.130	1.491	1.340	1.566	2.420	1.340	0.965	2.420	0.616	1.340	1.566
IFI-08	1.373	1.242	1.100	1.005	1.474	1.100	0.847	1.474	0.843	1.100	1.005
IG-01	1.345	1.325	1.097	0.926	1.289	1.097	0.952	1.289	1.028	1.097	0.926
IG-02	0.997	0.997	1.000	1.000	1.028	1.000	0.970	1.028	0.970	1.000	1.000
IG-03	1.131	1.171	0.967	0.999	1.188	0.967	0.985	1.188	0.986	0.967	0.999
IG-04	1.387	1.114	1.162	1.072	1.115	1.162	1.070	1.115	0.999	1.162	1.072
IG-05	1.104	1.625	0.680	1.000	1.649	0.680	0.985	1.649	0.986	0.680	1.000
IG-06	0.869	0.918	1.030	0.919	1.216	1.030	0.694	1.216	0.755	1.030	0.919
IG-07	1.519	1.326	1.047	1.094	1.384	1.047	1.048	1.384	0.958	1.047	1.094
IG-08	0.949	0.949	1.000	1.000	0.955	1.000	0.994	0.955	0.994	1.000	1.000
IG-09	1.150	1.273	0.934	0.968	1.236	0.934	0.996	1.236	1.030	0.934	0.968
IG-10	1.238	1.202	1.000	1.030	1.237	1.000	1.001	1.237	0.971	1.000	1.030
IIM-01	1.614	1.614	1.000	1.000	1.776	1.000	0.909	1.776	0.909	1.000	1.000
IIM-02	1.317	1.145	1.092	1.053	1.311	1.092	0.920	1.311	0.874	1.092	1.053
INB-02	0.787	1.143	0.903	0.763	1.080	0.903	0.808	1.080	1.059	0.903	0.763
INB-04	1.114	1.287	0.836	1.036	1.298	0.836	1.027	1.298	0.991	0.836	1.036
IPLA-01	1.125	1.084	0.993	1.045	1.151	0.993	0.985	1.151	0.942	0.993	1.045
IQOG-02	1.175	1.175	1.000	1.000	1.703	1.000	0.690	1.703	0.690	1.000	1.000
Mean	1.193	1.155	1.017	1.009	1.235	1.017	0.957	1.235	0.953	1.017	1.009
St. Dev.	0.347	0.167	0.137	0.102	0.282	0.137	0.105	0.282	0.102	0.137	0.102
Max	3.130	1.625	1.414	1.566	2.420	1.414	1.242	2.420	1.213	1.414	1.566
Min	0.787	0.835	0.680	0.739	0.824	0.680	0.631	0.824	0.616	0.680	0.739

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